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Sediment dynamics on the shore slopes of the Puget Island reach of the Columbia River, Oregon and Washington

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AN ABSTRACT OF THE THESIS OF Timothy Abbe for the Master of Science in Geology presented August 11, 1989.

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Water waves generated by wind and ships; ebb tidal currents; water level fluctuations; and dredging impact sediment transport in shallow water of the lower Columbia River. Observations were made over a one-year period after sand dredged from the navigation channel was placed at three study sites in the Puget Island region, 46°15'N

123°25'W, Oregon and Washington. Sediment composition is fine to medium grained, low density dacitic volcanics with small percentages of pumice, heavy minerals, and basalt.

Sediment response to ship waves was examined on a smooth sandy beach face at specific points in shallow water using a sediment trap system. "Ship waves" include: an initial drawdown event (uni-direction flow off the shore); a surge (transverse stern) wave moving obliquely up and along the shore in the direction of ship motion; "quiet" period (water surface returns to mean conditions); and incidence of secondary ship waves. Drawdown and secondary ship waves accounted for most of the sediment flux during ship passages. Hydraulics of ship wave actions include: (sheet flow, wave orbital velocities, plunging waves, and longshore currents. Boundary conditions describing the limit of shallow water sediment flux by ship waves are at a depth of about 2.0 meters to 0.3 meters above mean water level. A model constructed to evaluate the annual impact of ship waves showed that (using maximum measured merchant ship waves and natural processes), 6,364 m^3 of sand eroded or 25% of the 26,197 m^3 of sand place at the site. Using the maximum measured sediment transport by larger naval ship waves, predicted erosion is 73,478 m^3 of sand per year, above the eroded volume by 2.8 times. The range of predicted values encompasses the actual eroded volume.

Error is attributed to the exponential distribution of sediment flux in the vicinity of a breaking wave that makes accurate point sampling difficult. Another source of error in the mass balance may be the lack of observations during high energy events, such as storms.

Annual cumulative energy delivered by a process tote shore is secondary to instantaneous energy the process delivers. If instantaneous energy is not enough to move sediment then the process is of little importance in sediment transport. Observed ebb tidal currents and wind waves only slightly surpassed sediment threshold conditions, so even summed over large time periods, they account for a very small quantity of sediment entrainment. Ship waves regularly supply energy in very short time intervals (1-6 minutes) well in excess of the sediment threshold conditions and account for most o the sediment transport.

Physical processes also result in a distinct set of geomorphic features and sedimentary structures: shore notches, beach scarps, and planar bedding by ship waves; alluvial fans by wind; oscillatory ripples by wind waves; trough and hummocky cross-bedding by tidal fluctuations; swash lines of pumice and heavy minerals, beheaded ripples, and reactivation surfaces by waves. Shore slope change is most rapid shortly after sand disposal, decreasing with time as slope approaches a more stable state. The greatest

shore changes occurred at sites closest to the navigation channel. Features such as shore notches can dramatically impact slope evolution, eroding into a previously stable shore. Shore notches are asymmetric sites of accelerated shore erosion associated with adjacent lower beach accretionary lobes.

In water less than two meters, fluvial and estuarine processes are overprinted by pipeline dredging operations and the passage of large ships. Ship waves modify shore morphology and remove sediment from the intertidal zone of the shore slope.

SEDIMENT DYNAMICS ON THE SHORE SLOPES OF THE PUGET ISLAND REACH OF THE COLUMBIA RIVER, OREGON AND WASHINGTON

by

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This thesis means a lot to me, for it took perserverance I didn't think I could muster. My graduate studies at Portland State University have enabled me to become a better geologist, more organized, and the happiest I've ever been in my life! I'm looking forward to a challenging and productive career in environmental geology and engineering.

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INTRODUCTION

SYNOPSIS OF THE PROBLEM

What processes move sediment in shallow water along the shores of the lower Columbia River? How much bankline material sand is lost over time; how much sand is moved during events caused by ship passage? What is the shore and sediment response to processes observed? These are questions that have been addressed in this thesis.

Sand transport is an important physical phenomena in fluvial and coastal studies, directly impacting engineering endeavors within these settings. The lower Columbia River hosts a major deep draft navigation channel that is maintained through continual dredging. The source of shoaling sediments into the navigation channel has been a question engineers and scientists have attempted to answer for several decades. Local sediment sources within the river have only recently been considered the possible source for much of this shoaling (Eriksen, 1989).

The shallow near-shore zone may be a possible sediment reservoir (supplier) for channel shoaling and act as a geomorphic and sedimentologic recorder of the dominant physical processes. This hypothesis is examined using aerial imagery, surveying, sedimentology, sediment

transport studies, and established theory to evaluate the problem.

Lower Columbia sands exhibit a range of distinct sedimentary structures that result from a variety of distinct petrographies, physical processes, and grain size differences. The sites investigated were in shallow water inter- and supratidal regions along sandy shores of the lower Columbia River. Sediment transport initiated by water motions associated with the passage of ships was observed and analyzed.

The primary physical processes of the study region include: currents generated by tidal fluctuation and river discharge and wave actions generated by wind and ship passage.

The study setting is in northwest Oregon and southwest Washington between Columbia River Kilometers (RK) 54 to 88 (River Miles, RM, 34-55). See Figure 1. This area lies well upstream of maximum spring tide salinity penetration into the Columbia Estuary during low fresh water discharges, reaching RK 32 (Jay, 1984).

Many of the sandy shores along the banks of the Columbia are not natural, but disposal or "nourishment" sites constructed during dredging operations to maintain the Federal Navigation Channel. Dredging of the lower 178 kilometers of the Columbia has been going on since the late 1800's. The approximate mean annual volume of sediment

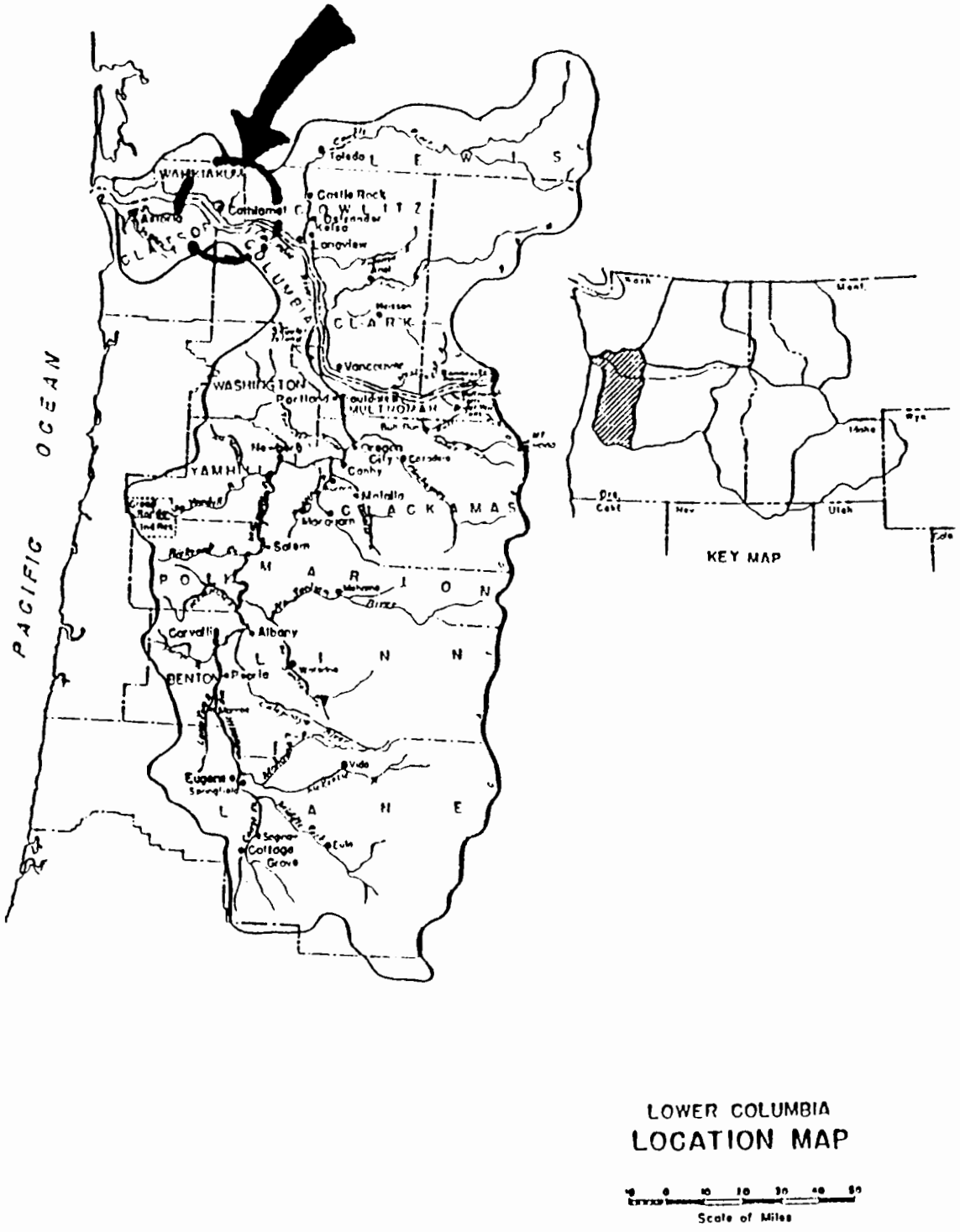


Figure 1. The lower Columbia River, USA. From USDI, 1947.

dredged from the Columbia River since the 1970's is between 5 to 6 millon cubic meters (USACE, 1988b). In order for channel maintenance procedures to be cost-effective and environmentally sound, the physical processes responsible for channel shoaling need to be understood. One facet of this comprehensive understanding is addressed by the observations and accompanying analysis of this study.

Currently there exists some question regarding the origins of the sediment responsible for channel shoaling: is the sediment derived from up-river sources or is it derived locally? Work by Eriksen (1988, 1989) suggests that most sediment responsible for shoaling is derived from local sources and enters the channel through side slope motion (for description of possible mechanics of this process, see; Ikeda, 1982). Shoaling may be due to natural bar migration and/or the erosion of unstable side slopes. Unstable side slopes are an artificial phenomena created by channel dredging and shore nourishments. If dredging operations are a precursor to mobilizing sediment back into the channel, then shoaling might be controlled by better dredging and nourishment practices. Eriksen (1988) reports that total sediment volumes produced in river dredging far exceeds average annual predicted sediment yields transported in the system.

GEOLOGY OF THE STUDY REGION

The study region lies at the margin between the North American continental plate and the subducting Juan de Fuca oceanic plate. The result of this collision has been active sedimentation, tectonic, and volcanic activity in the Pacific Northwest region for the last 55 million years (Lowry and Baldwin, 1952). Uplift in the northwest during the last five million years has resulted structural deformation (folds) and extensive faulting of the bedrock geology. The Coast Range of northwest Oregon and southwest Washington has been part of an accretionary prism for at least 45 m.y. (Heller and others, 1987).

The Holocene alluvial stratigraphy of the Columbia River valley is poorly documented, but in general consists of fine to medium grained volcanic sands interbedded with lenses of clay-silts.

Bedrock geology presents a record of deep to shallow water and subaerial deposits intercalated with basaltic sequences going back 50-60 million years ago (m.y.a.). The volcanic Cascade Range developed approximately 35 m.y.a. and has been the primary source terrain for sands transported through the lower Columbia River. Columbia River sand petrology is predominantly volcanic rock fragments (dacite and basalt) and plagioclase (Clemens and Komar, 1988; Abbe, 1988a; Sherwood and others, 1984; Whetton and others, 1969).

The May 8, 1980 eruption of Mount St. Helens is an example of the dramatic influence recent volcanism of the High Cascades has had on influx of sediments into the Columbia River; Hubbell and others, 1983, estimated that 27.5 million m^3 of sediment was contributed during the first 24 hours after the eruption. This sediment input reduced the 12.2 meter deep navigation channel to 4.3 meters at the mouth of the Cowlitz River, RK 109. The deposits spread 3.2 km downstream and 11.2 km upstream in the Columbia River (Hubbell and others, 1983). Table I presents the estimated sediment contributions of the Cowlitz River to the Columbia between 1980 and 1986 (USACE, 1988). Cowlitz River sediment is primarily clay, silt, or very fine sand. These fine sediment grains only account for a small fraction (<5% by weight; Hubbell and others, 1983) of the Columbia River sediment population composing the channel bed. The contribution of sediment by the Cowlitz to the Columbia is about two-thirds fine sand (.0625-.125mm) and one-third medium sand (.25-.50mm) (Eriksen, 1989).

Bed material is defined as the rock or sediment composing the channel bed. Bed material includes sediments transported as bedload (particles saltated along the bed) and suspended above the bed.

The lower Columbia's sediments coarsen upstream (Hubbell and others, 1983; Whetton and others, 1969). This trend generally lies within one standard deviation.

TABLE I

SEDIMENT CONTRIBUTION OF COWLITZ RIVER TO THE COLUMBIA RIVER AFTER THE ERUPTION OF MT. ST. HELENS

Columbia River Kilometer 109.5

Water	Sediment yield in millions of m^3		
Year	Total	Bed Material	Bed % of total
1980	30.6	N/A	N/A
1981	N/A	N/A	N/A
1982	17.59	0.76	4.3
1983	16.06	2.29	14.3
1984	7.65	1.53	20.0
1985	4.59	1.53	33.3
1986	3.82	1.53	40.0
1987	3.82	1.53	40.0

where bed material is grains larger than very fine sand (> 3Φ or .125mm, excluding v. fine sand).

Water Year = October to October

The Columbia River's western drainage basin (west of 122° longitude) is the primary source of coarse sediments (>.0625mm, sand and larger) found in the lower Columbia (Whetton and others, 1969). The construction of Bonneville Dam at RK 234 km has exaggerated this boundary and serves as the approximate upstream boundary of the "lower Columbia."

The lower Columbia has done extensive scouring (Allen, 1987) into the surrounding rocks, clearly evident

in the large basalt cliffs and canyons along the river's course. In the post-glacial period from about 18,000 years ago, the behavior of the river has probably been drastically different, filling in some of the valley that it had carved. A series of catastrophic floods about 13,000 years ago were responsible for much of the Columbia River's geomorphic expression.

The bedrock geology in the Price Island, Washington, region is exhibited in Figure 2 (Walsh, 1987). The region is characterized by volcanogenic sedimentary rocks and flows. A geologic cross section through the Columbia River valley at Price Island, WA (N46°15') is presented in Figure 3. The cross section shows a shallow, yet distinctly asymmetrical syncline. Strata on the Oregon side exhibit a relatively constant northerly dip of 10°, while the north limb of the syncline steepens from about south 10 degrees at Skamokawa, WA to about south 35 degrees 5 km to the north (Figure 3). The local bedrock foundation is partly composed of inclined strata of the Miocene Grande Ronde Basalt and underlying very fine to medium grained carbonaceous, micaceous sands of the Lower Astoria Formation (Figure 4).

The Columbia River Basalt Group is composed of a sequence of tholeiitic rift basalts that originated in Eastern Washington during the Miocene epoch. These basalts covered much of the Northwest, over an area of 163,721 km^2,

Figure 2. Geology of Price and Puget Island Reach. See key on next page. Adapted from Walsh (1987).

KEY TO GEOLOGIC UNITS PRESENTED IN FIGURE 2

STRATIGRAPHIC UNIT		AGE m.y.a.
Qal	(Quaternary alluvium)	<2
Qls	(Quaternary landslide debris)	<2
Qt	(Quat. terraced sediments)	<2
Tsp	(Saddle Mtns. Basalt)	16.6-11.2
Tgc	(Gnat Creek Formation)	" "
Tasu	(Upper Astoria Formation)	" "
Twf	(Wanapum Basalt, Frenchman Springs mem.)	" "
Tiwf	(Intrusive Frenchman)	" "
Tgr	(Grande Ronde Basalt)	" "
Tigr	(Intrusive Grande Ronde Basalt)	" "
Tasc	(Cannon Beach mem. Astoria Fm-Niem & Niem, 1985)	24.0-11.2
Tasw	(Wickiup Mtn. mem. (Niem and Niem, 1985))	" "
Tasl	(Lower mem. of Wells)	" "
Tsmc	(Smuggler Cove Fm. of Niem and Niem, 1985)	30.0-17.0
Tlcs	(Lincoln Creek Fm., sandstone member)	38.0-39.0
Tsc	(siltstone of Skamokawa Creek of Wells, 1981)	40.0-36.6

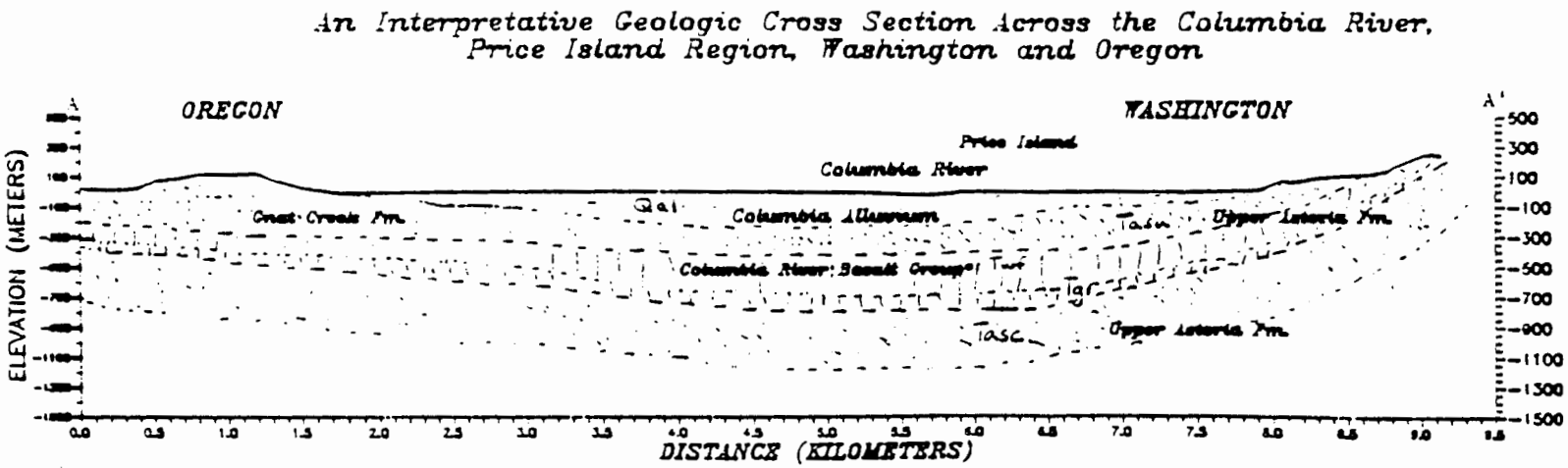


Figure 3. Geologic cross-section. Through Price Island, Washington.

Figure 4. Local geology. Steeply dipping bedding east of Cathlamet, WA; north of Puget Island along Washington Route 4. Grande Ronde basalt overlying sands of Upper Astoria Formation.

and have an estimated cumulative volume of 170,649 km^3 (Tolan and others, 1987). Some of these flows used the ancestral Columbia River basin as their primary flow path to the west. Thus, the morphology of the Columbia's ancestral valley limited the lateral extent of the basalt flows and the flows subsequently influenced the river's course (McKee, 1972).

On the Oregon side of the Columbia River across from Puget Island, the Gnat Creek Formation outcrops above approximately 40 meters of the Frenchman Springs basalt member of the Columbia River Basalt Group. The Gnat Creek Formation (Tgc) consists of friable, cross-bedded or bioturbated, micaceous and carbonaceous feldspathic sandstone, pebbly, coarse grained feldspathic sandstone, thick bedded massive sandstone with slumped siltstone blocks in channels cut into laminated carbonaceous mudstone, and rare lignite, a low grade coal (Walsh, 1987). The Gnat Creek Formation appears to be correlative in general lithology and age to the Upper Astoria Formation on the Washington side. The Gnat Creek Formation overlies the Frenchman Springs Basalt member of the Columbia River Basalt Group. The friable, poorly lithified nature of the Gnat Creek and Astoria Formations is characteristic of much of the sedimentary stratigraphy in Northwest Oregon and Southwest Washington.

THE COLUMBIA RIVER

The Columbia River drains an area of 671,000 km^2 (259,000 mi^2), flowing from the Canadian Rockies to the Pacific Ocean. Columbia River discharges for the study period are presented in Table II. Fresh water flows generally range from 4,000 to 15,000 m^3/s. Salt water intrusion can directly impact sediment transport by increasing the water density and thus transport potential (Dyer, 1986). Salt intrusion into the Columbia Estuary can reach RK 38 (RM 24) during the low flow season, but is downstream of Astoria during high freshwater flows (Jay, 1984). Figure 5 presents monthly mean discharges for the time periods listed in Table II.

In any hydrologic and sediment transport study in the nearshore boundary region of a river, it is important to establish channel geometry and water surface elevation. Flood events will raise the water level on the shoreline and thus where currents and wave actions will occur. Much of the shoreline damage in coastal regions occurring during storms is not by the increase in water level, but the elevated wave actions (USACE, 1984; MuirWood and Fleming, 1980; Bascom, 1980). The frequency in which particular elevations are subjected to shoreline processes can be predicted using stage elevation estimates for combined flood events. (USACE, 1986). Floods increase sediment

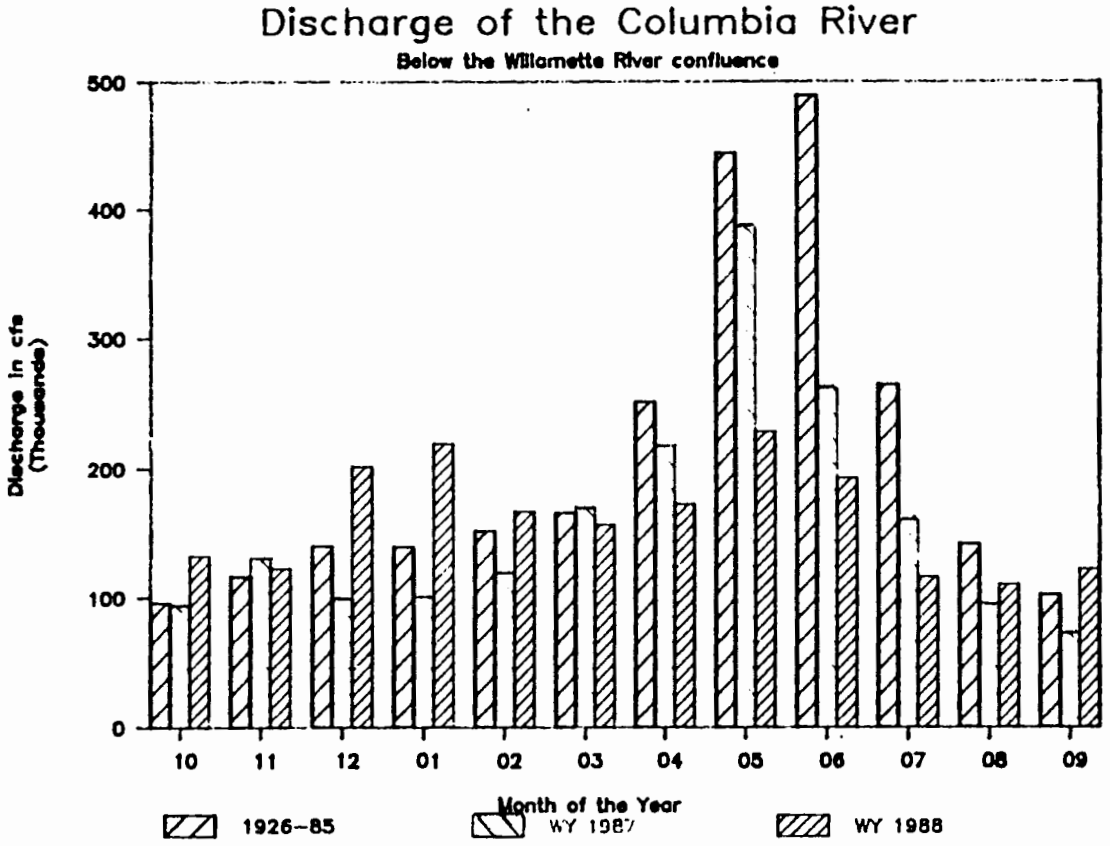


Figure 5. Discharge of the Columbia River. Water years 1987 and 1988. Monthly average discharge from 1926 to 1985.

TABLE II

DISCHARGE OF THE COLUMBIA RIVER

Downstream of the Confluence with the Willamette River

Water Year (Oct. to Sept.)	Mean Annual Discharge	Maximum Discharge	Minimum Discharge
1926-1985[1] average	5,905 m^3/s (208,516cfs)	13,837 m^3/s (488,651cfs) (June)	2,717 m^3/s (95,944cfs) (October)
1987[1]	4,503 m^3/s (159,030cfs)	10,926 m^3/s (385,860cfs) (May)	2,026 m^3/s (71,530cfs) (September)
1988[2]	3,845 m^3/s (135,866cfs)	6,938 m^3/s (245,013cfs) (May)	2,223 m^3/s (78,551cfs) (July)

[1]CRMWG, 1988
[2]USGS, 1989

transport and elevate shoreline processes to regions otherwise unexposed to these actions.

Other processes associated with flood events include increased bed shear and sediment transport. Bedload transport in the Columbia only becomes appreciable with significant discharges. If the Columbia has a discharge of 7,080 m^3 (250,000 cfs), predicted bedload is less than 1 ton/day; at 8,500 m^3 (300,000 cfs) predicted bedload is about 1.5 metric tons per day or about 2 m^3 of sand/day (USACE, 1986).

Tides in the region are mixed semidiurnal. Every day there are two high tides of distinctly different elevations, likewise for the low tides. The average

maximum difference between lower low tide and higher high tide is about 2 meters during neap tides and up to 4 meters during spring tides. Tidal effects are felt all the way up the Columbia River to Bonneville Dam, RK 234.1 (RM 145.4). Tides are very important in the evaluation of sediment dynamics because they control water elevation, cross-sectional channel area, salt water intrusion, and the velocity regime of the river.

High and low water slack correspond to static water conditions in the river, which are the times between ebb and flood flow. Slack conditions do not coincide with high and low water surface elevations in the Puget Island Region. Slack water is when current velocity is zero. Maximum flood and ebb currents occur 1 to 2 hours before high tide and low tide, respectively. Slack water occurs 1 to 2 hours before and after peak flood flow.

GEOMORPHOLOGY

The Lower Columbia flows through a confined alluvial plain from the Cascade Mountains to the Pacific Ocean. The Lower Columbia is characterized by large curves extending to the sides of its valley. Structural features such as fault trends and basalt outcrops apparently control much of the river's lateral migration. The strong influence of geology upon the river's character is attributed to active tectonics. The sedimentary stratigraphy of the lower

Columbia River valley is a fascinating record of Pleistocene to Recent geologic processes. The most dramatic sedimentary processes that have affected the river's morphology and sediment transport have been:

- a series of extremely large floods called the Bretz Floods that occurred in the late Pleistocene and Early Holocene (Allen, 1986);
- the rise in sea level since the Flanarian Stage of the Wisconsin Ice Age 18,000 years ago;
- Holocene (pre-human influence) flood events;
- human influences (though the time period has been very short in comparison and evaluation is difficult).

Sea level rise has the same general sedimentologic effect as damming a river. The river responds by aggrading its bed in an upstream direction, illustrated with a simplified cartoon in Figure 6. Alluvial sands were found to depths of at least 90-100 meters in Cathlamet channel (Figure 7), providing some evidence that the lower Columbia became a sediment trap due to the backwatering effect of a sea level rise (Washington State, 1986). An aggradation of approximately 100 m of recent sediments corresponds to sea level changes in the last 18,000 years. Shepard (1963) used C^{14} dates of peat, wood, and shells deposited near sea level and now submerged, to estimate a rise of approximately 100m in sea level. Curray (1965) had come to

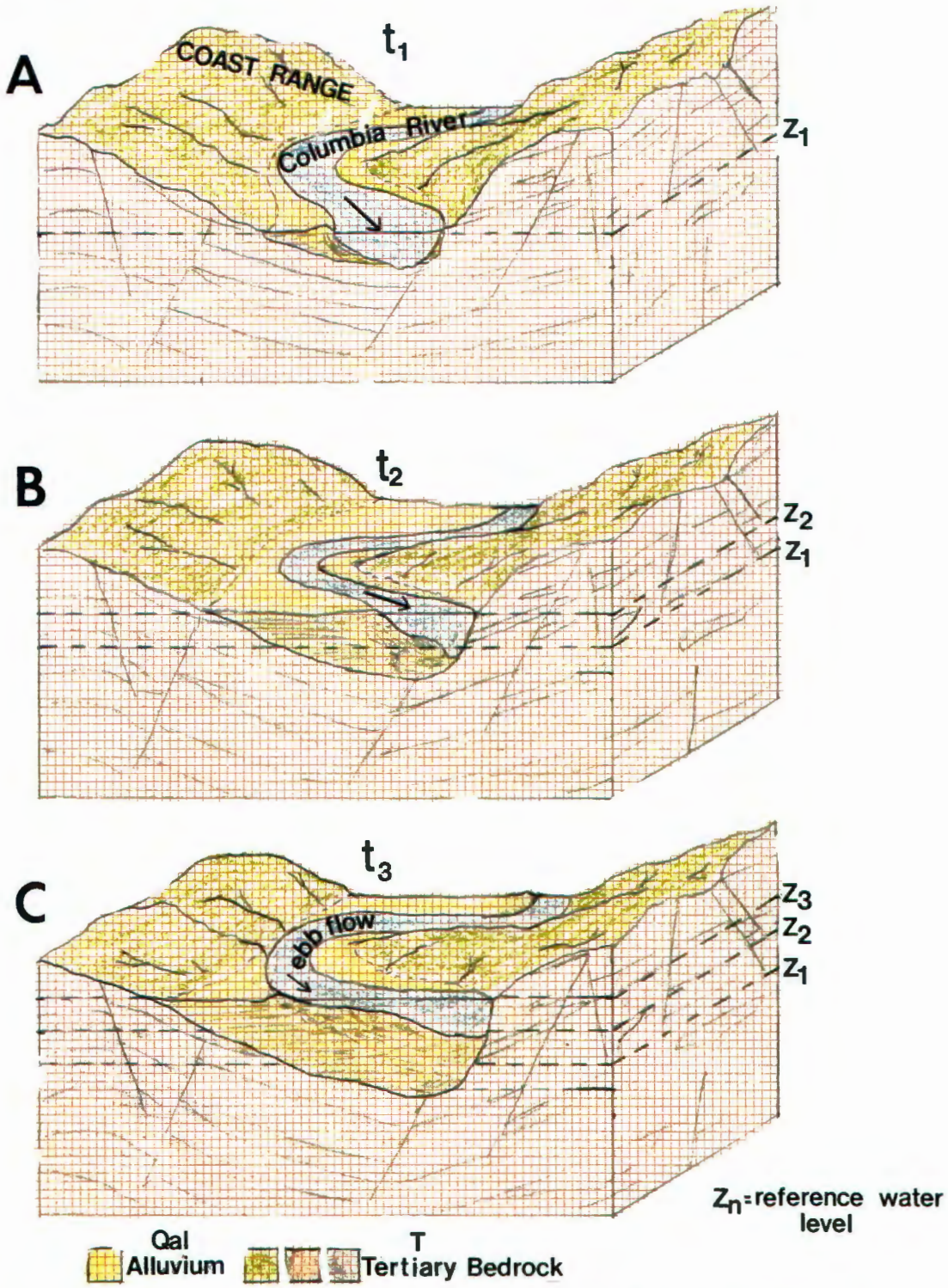


Figure 6. Quaternary history of the lower Columbia River valley. In this hypothesis the Columbia River remained entrenched in the same approximate location on the alluvial plain throughout the rise in sea level.

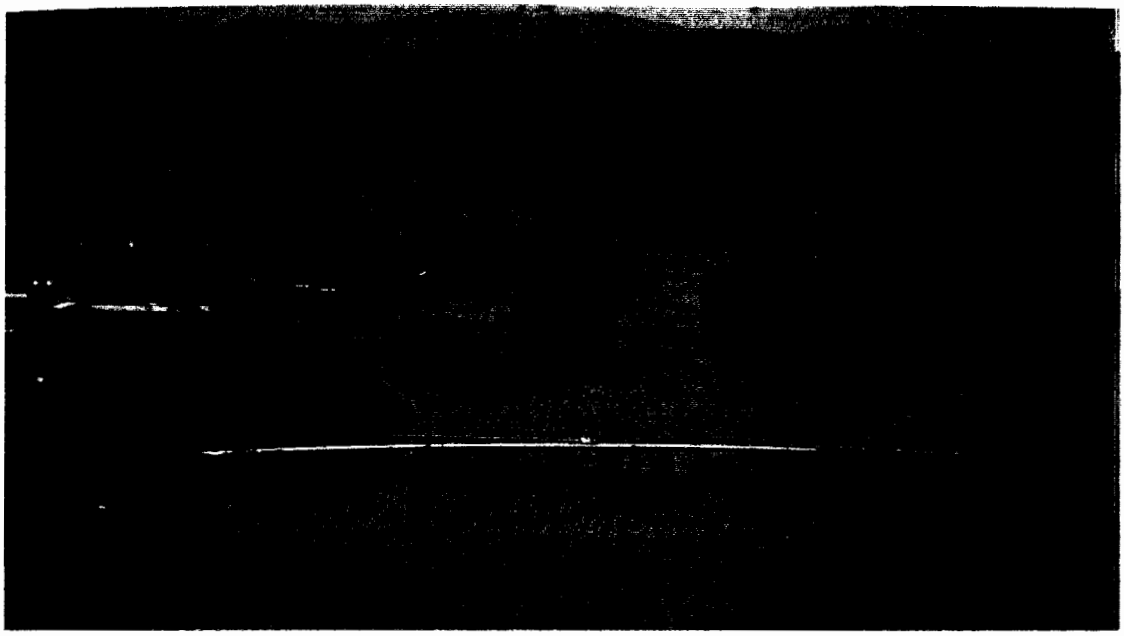


Figure 7. Puget Island study site from Cathlamet, Washington. In foreground is new Puget Island Bridge, from which piling logs recorded Columbia River sand (Holocene) to depths of slightly less than 100m (285 ft). Main channel flows left to right just above center of photograph. Cathlamet Channel is in center foreground.

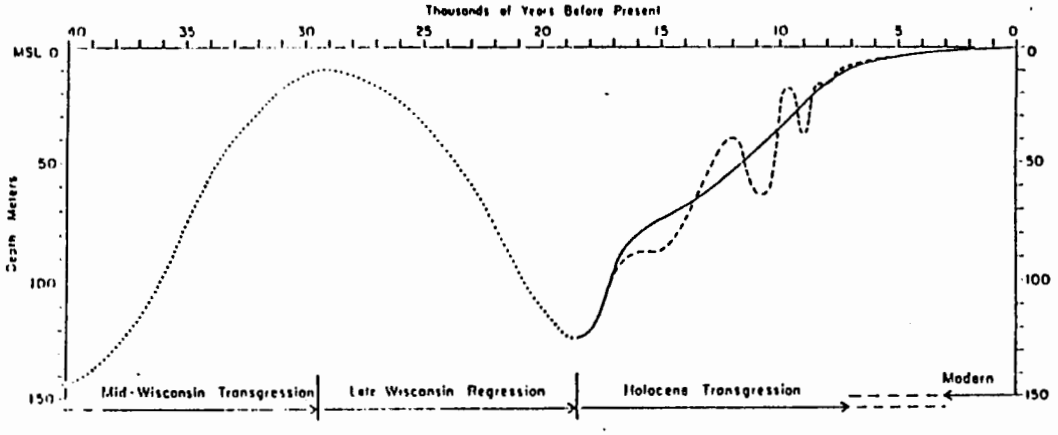


Figure 8. Holocene sea level rise. Since the Wisconsin Ice Age. From Curray (1965).

a similar estimate, graphically illustrated in Figure 8 (Komar, 1976). The rate of sea level rise have been estimated at about 5-7 mm/yr following the retreat of the last glaciation 9,000-5,000 years ago (Curray, 1965); rates that have been proportional to the rate of sedimentation in the lower Columbia River valley. Further evidence of the rise in sea level and aggradation in the lower Columbia River valley (thus lack of sand flux to the coast) comes from studies of sands along the Oregon Coast (Clemens and Komar, 1988; Peterson and others, 1985). Clemens and Komar (1988) concluded that the Columbia has not provided a sediment supply to the Oregon coast south of Cape Flattery since the Pleistocene.

Human Actions

Human activities have been extensive and have affected the behavior of the lower Columbia River. Table III lists chronologically major engineering projects on the Columbia River system. An extensive reservoir network regulates flows to produce electricity and provide flood control. Flow regulation cuts down the number of major flood events responsible for the greater part of sediment transport in a river. The impact of engineered structures on the Columbia is illustrated in the flow duration curves from 1878-1962 and 1972-1977, (Figure 9). The Columbia River's estimated average annual sediment yield at Vancouver has been reduced by the regulation (Figure 9)

TABLE III

MAJOR HUMAN INFLUENCES ON THE LOWER COLUMBIA RIVER

DATE	ACTIVITY
pre 1885	Sporadic, minimal dredging
1885	30 ft (10m) Entrance Project initiated
1905	40 ft (12m) Entrance Project initiated
1938	Bonneville Dam
1945	Regular annual dredging initiated
1954	48 ft (14.6m) Entrance Project initiated
1977	52 ft (16m) Entrance Project initiated

Modified from: Sherwood and others, 1984.

from «10,700,000 m^3 before 1962 to 1,530,000 m^3 by the late 1970's (USACE, 1986). After the May 1980 eruption of Mt. St. Helens, the sediment budget has greatly increased for the Columbia downstream of the Cowlitz River confluence from 5,350,000 m^3 to 19,110,000 m^3 (with a bed material fraction of between 1,070,000 m^3 and 2,750,000 m^3 a year).

Pre-1980 sediment predictions were about 1,530,000 m^3 with a bed material fraction between 306,000 m^3 to 459,000 m^3 (20-30% of the total) (USACE, 1986).

Extreme events in fluvial systems (floods) that occur about 5% of the time and account for 90% of the sediment discharge. About 80% of the time, base flow conditions of a river contribute virtually nothing to its overall sediment discharge (Dyer, 1986). Water regulation also

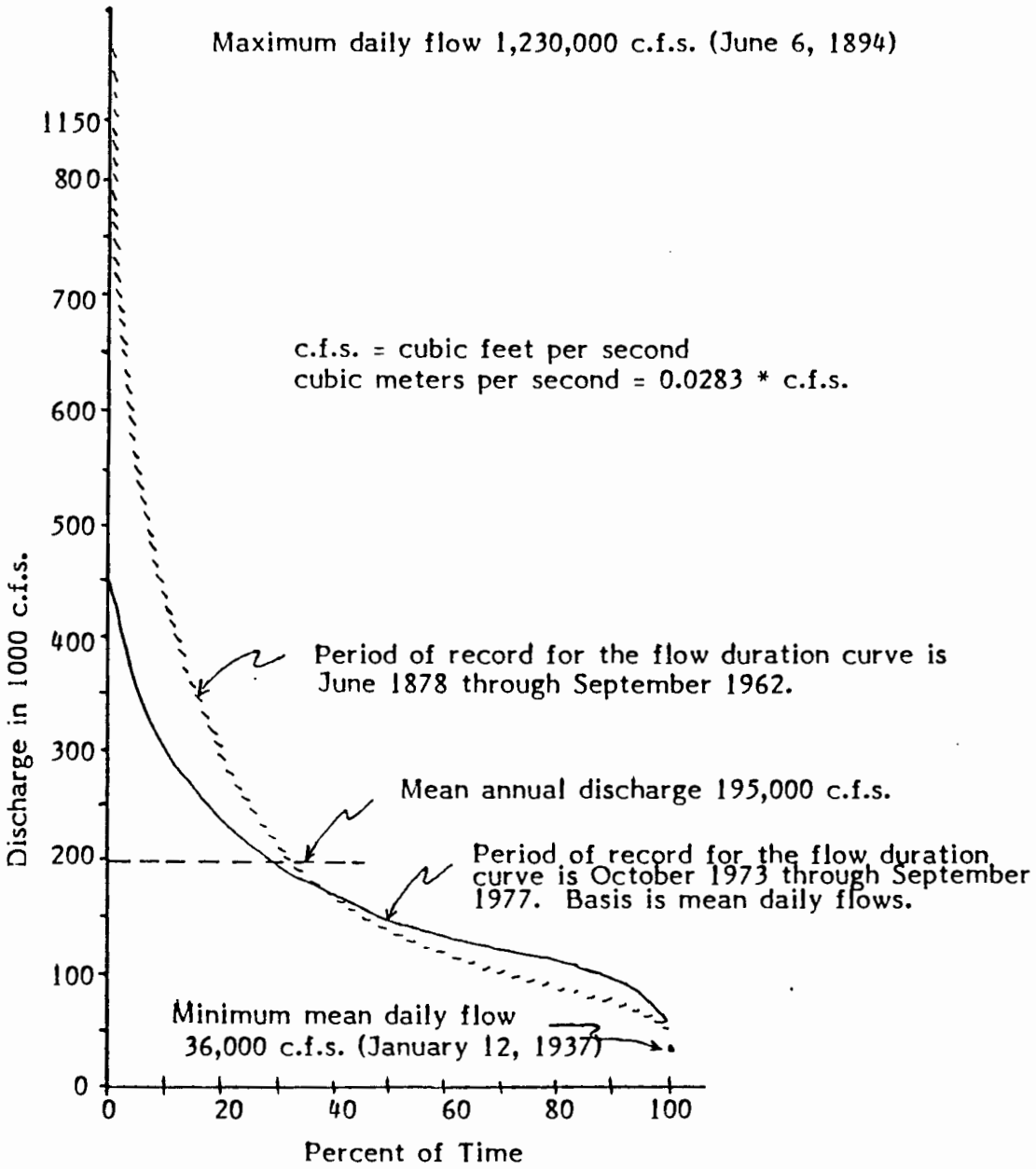


Figure 9. Flow duration curves. Columbia River at the Dalles, Oregon before and after regulation (USACE, 1986).

affects the water elevation, thus affecting where nearshore processes will occur.

To maintain the Federal navigation channel to the current specified dimensions of 40 x 600 feet (12.2 x 182.9 meters), the U.S. Army Corps of Engineers uses both hopper and pipeline dredging operations. The majority of river dredging (upstream of the Columbia River mouth) is done by the pipeline method which uses shore sites for depositing channel sands.

Shore Features

Shorelines exhibit distinct geomorphic characteristics dependent on the sediment composing them and the processes acting upon them. The shore slope is controlled by the energy assault upon it and the sediment particle size (Komar, 1979). These subenvironments and associated features in the near-shore shallow water region presented in Figures 10 and 11 (definitions from Bagnold, 1963; and Komar, 1976).

SHIP WAVES

When discussing the physical processes acting in the Lower Columbia, those originating from the passage of a large vessel cannot be ignored. The Lower Columbia is a major international shipping lane, with the highest bulk export tonnages on the west coast and second largest (in

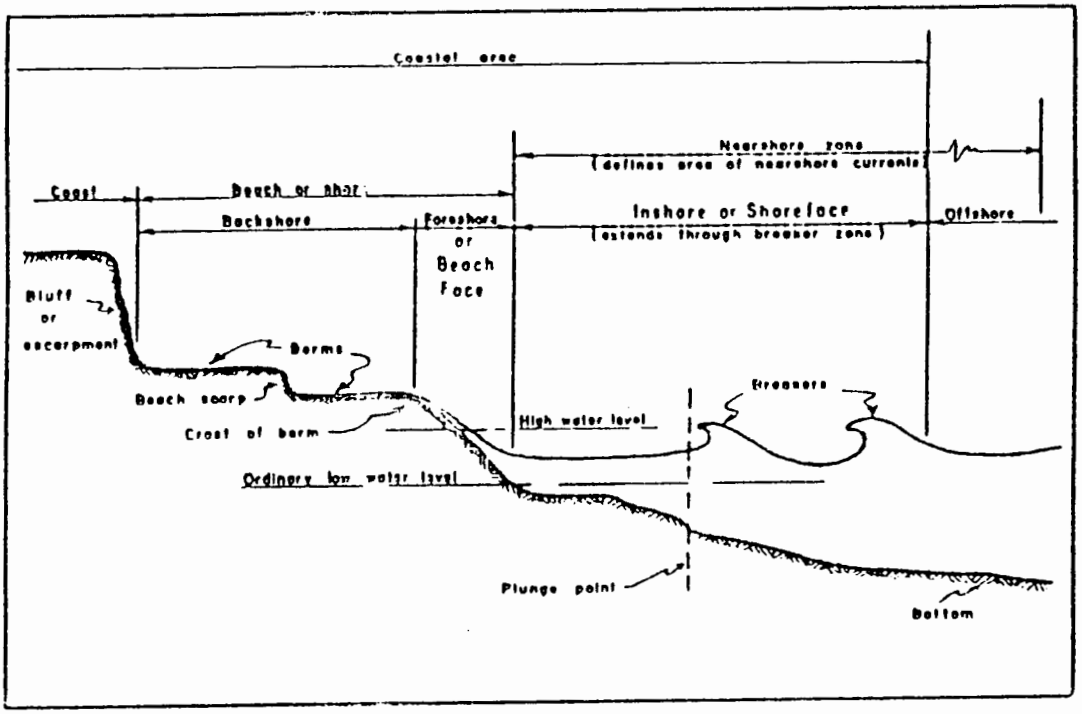


Figure 10. Beach profile-related terms (USACE, 1984).

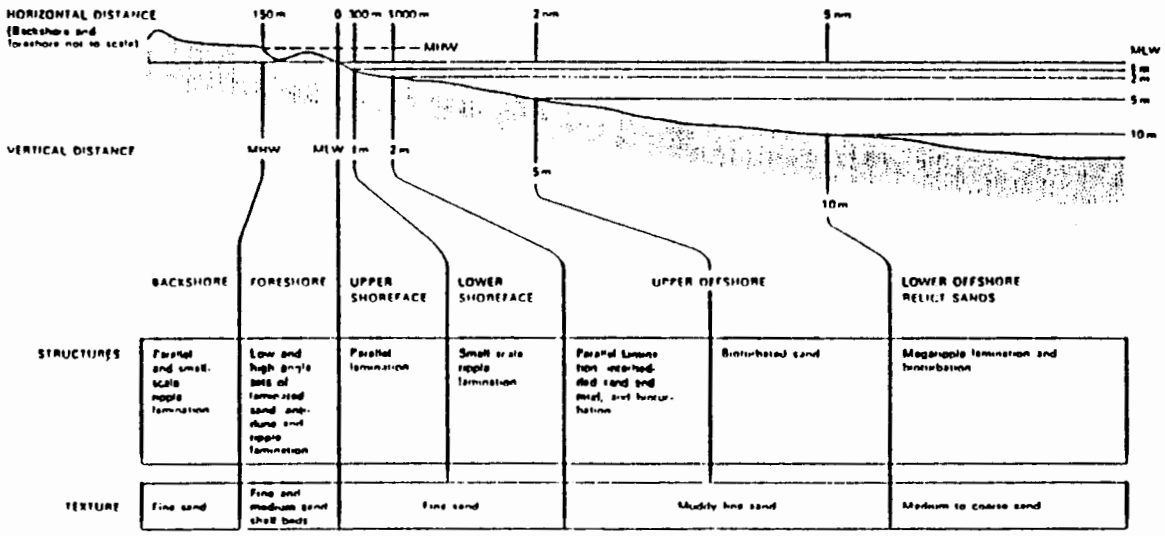


Figure 11. Sediment and bedform characteristics of a coastal near-shore zone, features also observe along the lower Columbia River beach nourishments (Reading, 1978).

tonnage) inland navigation system in the United States. The number of deep draft ships using the Columbia navigation channel increased sharply after the official channel enlargement in 1976 (Port of Portland, 1986).

When a large ship moves through a confined channel, a complex set of water waves occur. This set of waves moves with the velocity of the ship along the banks of the channel, with a wide range of behavior that is dependent on the channel geometry and shallow water region close to shore. Water motions associated with vessel passage in a confined channel are presented in Table IV (Span and others, 1981). The behavior of water waves attacking a shoreline has been documented in coastal studies (Figure 12) and can be used as an analogy in evaluating the behavior of ship waves.

The magnitude of ship waves is a function of several variables; as presented below (Ofuya, 1970):

$$H_{max} = f(L_s, Y_s, V_s, d, D, B, g) \quad (1)$$

where: $f(\ )$ = function of ...

Y_s = distance from ship's sailing line

L_s = length of ship

V_s = velocity of ship

d = depth of water in channel

D = ship's draft

B = width of ship (beam)

g = acceleration of gravity

TABLE IV

SET OF WATER MOTIONS ASSOCIATED WITH
SHIP PASSAGE IN A CONFINED CHANNEL

1) the return flow between the ship and the canal bottom and banks.

2) the drawdown (depression of water surface) caused by the return flow, sometimes called the primary ship wave.

3) the transverse stern wave, being the transition between the drawdown alongside ant the (slightly raised) water surface behind the vessel. When pronounced, such a wave is comparable to a surge wave.

4) the slope-supply flow providing water over the canal slopes to restore the original water level immediately after the ship has passed.

5) the secondary ship waves (predominantly bow and stern waves).

6) the propeller race.

(Span and others, 1981)

a similar estimate, graphically illustrated in Figure 8 (Komar, 1976). The rate of sea level rise have been estimated at about 5-7 mm/yr following the retreat of the last glaciation 9,000-5,000 years ago (Curray, 1965); rates that have been proportional to the rate of sedimentation in the lower Columbia River valley. Further evidence of the rise in sea level and aggradation in the lower Columbia River valley (thus lack of sand flux to the coast) comes from studies of sands along the Oregon Coast (Clemens and Komar, 1988; Peterson and others, 1985). Clemens and Komar (1988) concluded that the Columbia has not provided a sediment supply to the Oregon coast south of Cape Flattery since the Pleistocene.

Human Actions

Human activities have been extensive and have affected the behavior of the lower Columbia River. Table III lists chronologically major engineering projects on the Columbia River system. An extensive reservoir network regulates flows to produce electricity and provide flood control. Flow regulation cuts down the number of major flood events responsible for the greater part of sediment transport in a river. The impact of engineered structures on the Columbia is illustrated in the flow duration curves from 1878-1962 and 1972-1977, (Figure 9). The Columbia River's estimated average annual sediment yield at Vancouver has been reduced by the regulation (Figure 9)

TABLE III

MAJOR HUMAN INFLUENCES ON THE LOWER COLUMBIA RIVER

DATE	ACTIVITY
pre 1885	Sporadic, minimal dredging
1885	30 ft (10m) Entrance Project initiated
1905	40 ft (12m) Entrance Project initiated
1938	Bonneville Dam
1945	Regular annual dredging initiated
1954	48 ft (14.6m) Entrance Project initiated
1977	52 ft (16m) Entrance Project initiated

Modified from: Sherwood and others, 1984.

from «10,700,000 m^3 before 1962 to 1,530,000 m^3 by the late 1970's (USACE, 1986). After the May 1980 eruption of Mt. St. Helens, the sediment budget has greatly increased for the Columbia downstream of the Cowlitz River confluence from 5,350,000 m^3 to 19,110,000 m^3 (with a bed material fraction of between 1,070,000 m^3 and 2,750,000 m^3 a year).

Pre-1980 sediment predictions were about 1,530,000 m^3 with a bed material fraction between 306,000 m^3 to 459,000 m^3 (20-30% of the total) (USACE, 1986).

Extreme events in fluvial systems (floods) that occur about 5% of the time and account for 90% of the sediment discharge. About 80% of the time, base flow conditions of a river contribute virtually nothing to its overall sediment discharge (Dyer, 1986). Water regulation also

> The importance of these processes differs with regard to bottom and slope loading as a function of speed, canal dimensions, and ship's size.

This statement has been reiterated in regard to specific situations throughout the world both in canals and natural river systems. Johnson (1958, p. 666) stated;

> Ships moving through water generate surface waves which in many navigation channels cause severe wave-wash damage to the bank.

Hertzberg (1954, p 628) found wave-wash damage along narrow unprotected foreshore of the Mississippi River: "Destructive waves in the river are caused by wind and passing ships." Hertzberg (1954) suggested that shore debris such as logs enhance erosion. This debris is common along the Lower Columbia River. Ship generated water motions have been recognized as a significant set of forces eroding the boundaries of many of waterways in the Soviet Union.

Bekendam and others (1988, p. 21) evaluated barge traffic in the River Rhine for the Netherlands Government in an extensive study of the channel-vessel physical processes. The study concluded that:

> Navigation has a big impact on the natural environment of the river bank. To prevent further degradation of the natural environment and the particular river landscape, measures are necessary to reduce wave attack and the force of currents (Bekendam and others, 1988).

Their investigation was instigated because of an increase in the size of barges using the navigation route.

The state of Maryland Coastal Resource Division (1981) studied the impacts of small boats on banks and found that in constricted channels having no speed limits, the boat wakes played an active role in bank erosion.

Ship waves in the lower Columbia have been recognized (Abbe, 1988, 1989; Abbe and Phan, 1987; Beeman, 1985a, b; USACE, 1960, 1986) as an agent in shore erosion. Figure 15 exhibits shore protection installed by a land owner on Puget Island, WA, to protect a rapidly retreating beach scarp that jeopardized the land owner's residence. Most of the studies to date described the secondary wave train of vessels and did not present the complete set of processes occurring with a ship passage such as drawdown and return wash (surge) or the relative impact of these forces on sediment transport and shore morphology (PIANC, 1987).

Shore protection at the Puget Site in at the apex of a "shore notch" (site of accelerated bank erosion) that was threatening a house (Figure 13). Sand accumulated on the shoreward side of the structure. Ship surge and waves eroding the shore notch at this site carry sediment from downstream (right to left), building out a beach accretionary lobe to the left. This longshore transport is also suggested by the accumulation of sand behind the structure. The structure did aid in preventing further transgression of the beach scarp.

Much of the theoretical model work and field work examining ship generated hydraulics in a confined channel is based on a canal setting. The canal is a designed structure with a static morphology through which flow velocities are usually negligible. The static-steady state nature of canals differentiates them from rivers. The natural river's morphology is controlled by its geologic setting, sediment load and basin hydrology. In the United States, the vast majority of the navigable waterways are natural rivers. Structures have been built in these navigable rivers to obtain a more consistent and predictable behavior of the river. Groins, pile dikes, and shore revetments attempt to train thalweg currents into a consistent position to protect shorelines and maintain a navigable channel. Reservoir networks further control rivers by regulation of discharge and sediment retention.

HYPOTHESIS

This study investigated the hypothesis that shore nourishment stability is expressed in the shore's morphology with respect to time and the physical processes attacking the site. Three important concepts are presented in this hypothesis:

1) Shoreline sedimentary features reflect the prevailing physical processes.

Figure 13. Shore protection. Installed by land owner at Puget Island site, at the upper left portion of the beach below the residence.

2) The primary processes are water motions due to river and tidal currents and wave actions due to wind and ship passage.

3) Shoreline stability can be predicted by understanding these physical processes.

In order to establish the significance of this hypothesis, the study has described examples of: shore morphology, shore changes over time, the effect of dredged channel sand disposal and the disposal (or nourishment) response to specific processes, shore sediment, and sediment transport induced by ship generated water motions. Using site specific observations, the study presents part of the sedimentology and hydraulics in a shallow water

setting of a tidally affected river hosting extensive human activity.

METHODS

GENERAL METHODOLOGY

The study utilized several different investigative methods at several different scales to approach and solve the problem. Background data in the form of aerial imagery and topographic/bathymetric maps were examined over time. Sites chosen for examination were surveyed over a one year period. Physical processes were observed at the sites and ship waves were quantitatively measured. Geomorphic features and sedimentary structures were observed and recorded. The sediment was analyzed for size distribution and petrography.

The first step in the methodology to investigate sediment transport was to apply appropriate theoretical and empirical relationships to see if measured physical processes in the study region were likely to be responsible for sediment transport. The second step was to measure sediment transport in the regions of concern. Physical measures made of wave heights, beach slope, wave period, depth and wave incidence were plugged into established expressions describing wave hydraulics and sediment transport to predict the thresholds of sediment motion.

Methods used in this study to evaluate sediment dynamics on the shore slopes of the lower Columbia are as follows:

1 - Establish site locations and document site evolution.

2 - Observation and description of sedimentary forms and their creation and destruction.

3 - Establishment of processes occurring and their basic parameters.

4 - Description of sediment population to obtain basic information necessary for to evaluate of sediment transport.

5 - Use of basic wave and current measurements to see if threshold conditions are expected to be surpassed. Make predictions of the relative importance of sand transport due the various processes observed.

6 - Design of sampling scheme to evaluate sediment transport.

7 - Measurement of sediment transport on beach face and develop simple model to estimate total transport.

To examine shore slope sediment dynamics, specific sites needed to be chosen. Selection of these sites was based on the following criteria:

o A current beach nourishment site

- Location along the navigation channel
- Accessibility

Field reconnaissance and review of dredging operations lead to the selection of four study sites. These sites were than further divided by the detail in which they would be examined. The most accessible site would be examined with the most detail; profiling, geomorphic records, current and tidal records, ship wave records, and sediment transport observations. Two other sites would be include profiling and geomorphic observations and the fourth site would include only occasional visual observations.

SHORE MONITORING

Aerial Image Analysis

Aerial imagery was used to see long-term trends along the shores of the study sites. The images were stereoscopic black and white or color infrared photographs at a scale of 1:11,111. Images were equilibrated to the same scale using a zoom transfer scope. Polygons representing the change in area over time were digitized to find their areas. Only polygons of area change on the navigation side of Price Island were used in determining the area loss over time. Other areas were determined to experience minimal change and were not evaluated.

Profiles

Shore profiling is an essential component of most coastal and fluvial problems. Simple level and rod surveys were used to describe the shore sites. A surveying reduction software package (Birkemeir, 1988) and hand calculations were used to derive and present shore changes over time.

1) Field surveys (level and rod).
2) Stereoscopic orthophotography (from aerial photographs).

A simple leveling profile, as presented in Figure 14 is a quick, inexpensive and accurate technique for documenting slope evolution. Profile data such as that illustrated in Figure 15 were digitally input into a computer for analysis and graphical presentation. These profiles were plotted on a planimetric grid so that three dimensional analysis of beach sediment volume changes could be done. Each profile had an established benchmark stake.

When these profiles are entered into a database with appropriate elevation corrections, the development of slopes can be analyzed for distinctive trends (Figure 16). These trends can lead to empirical expressions that could be used in predictions and modeling.

Level and rod profiles of the beach nourishments were done for a period of approximately one year to show slope and volume changes over time. Beach slope is an integral

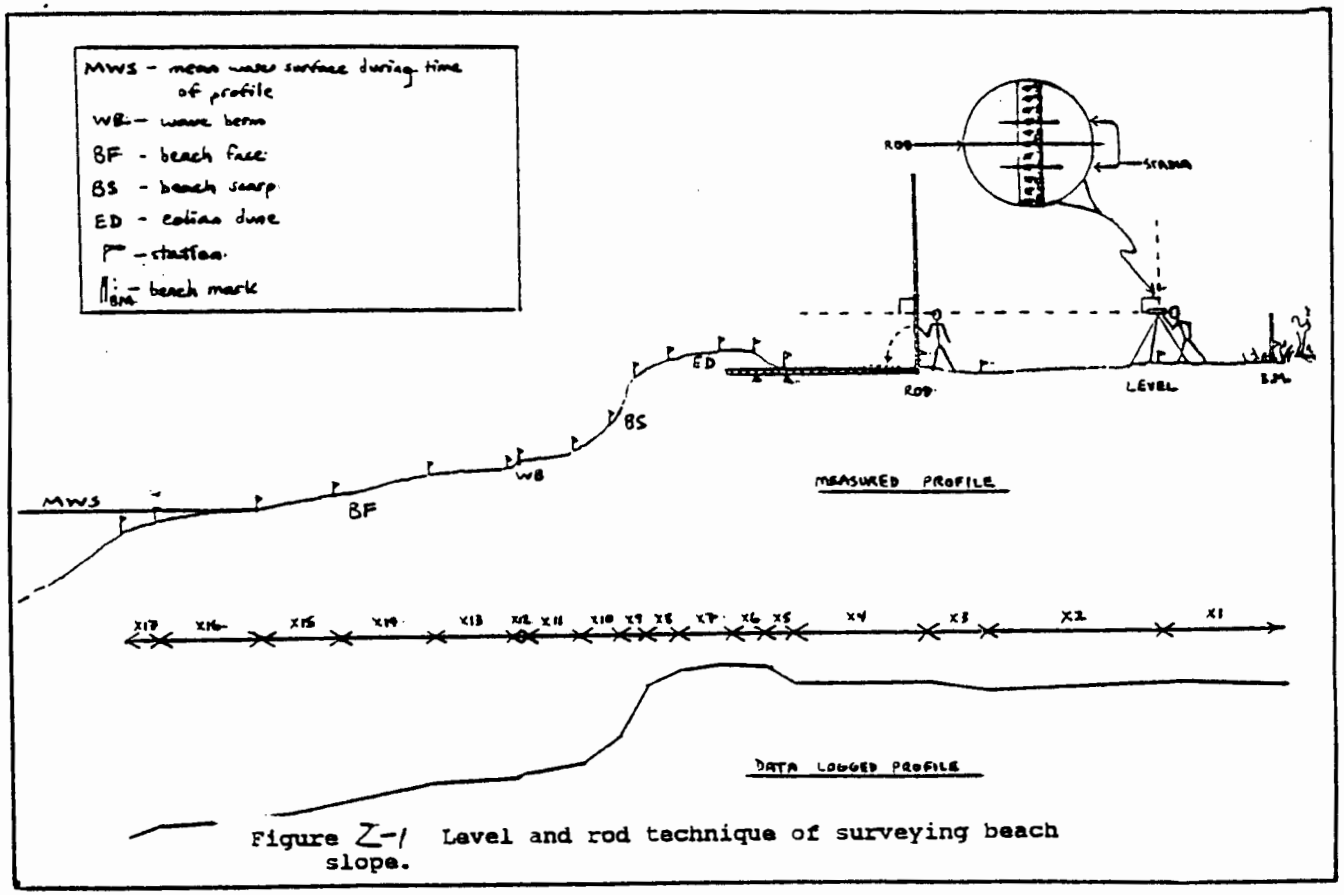


Figure 14. Surveying beach slope.

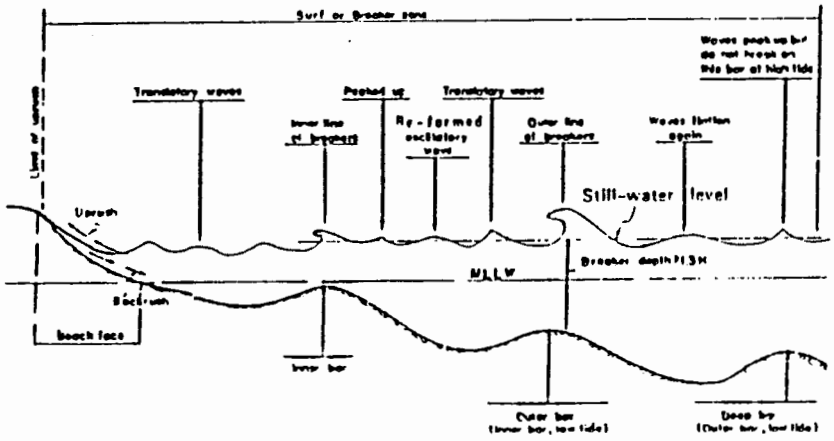


Figure 12. Waves in the breaker zone. From USACE (1984).

The importance of ships moving in inland waterways is brought out clearly in this excerpt from Fuehrer, Romisch, and Engelke (1981, p. 30):

> In last the two decades (1960-80) the problem of the hydraulic loading on the bottom and slopes of navigation canals by shipping traffic has gained an increasing politico-economic importance on the account of the rapid development of inland navigation. The inland waterways are exposed to an increased hydraulic loading by:
> - increasing size of ships
> - increased power and thus speed of ships
>
> In canal reaches with heavy traffic the above mentioned development leads to suddenly increasing damage of the bottom and slopes, thus causing rather high maintenance cost.
>
> The following hydraulic effects produced by the moving ship are above all responsible for the destruction of the canal boundaries:
> - wave motion caused by ships
> - displacement current (backwash)
> - flow processes caused by propeller (jet)

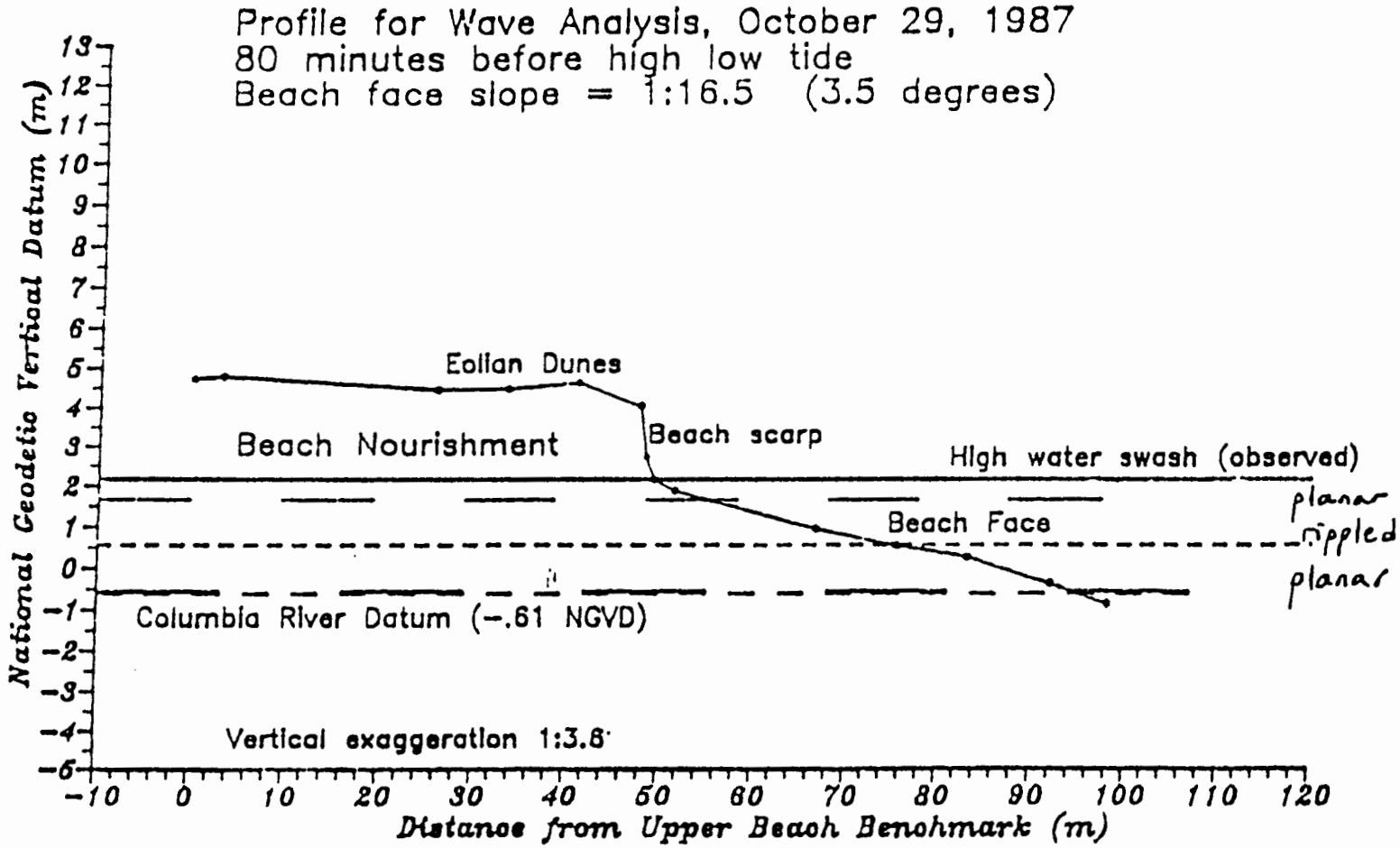


Figure 15. Typical shore profile. As presented from rod and level profiling data.

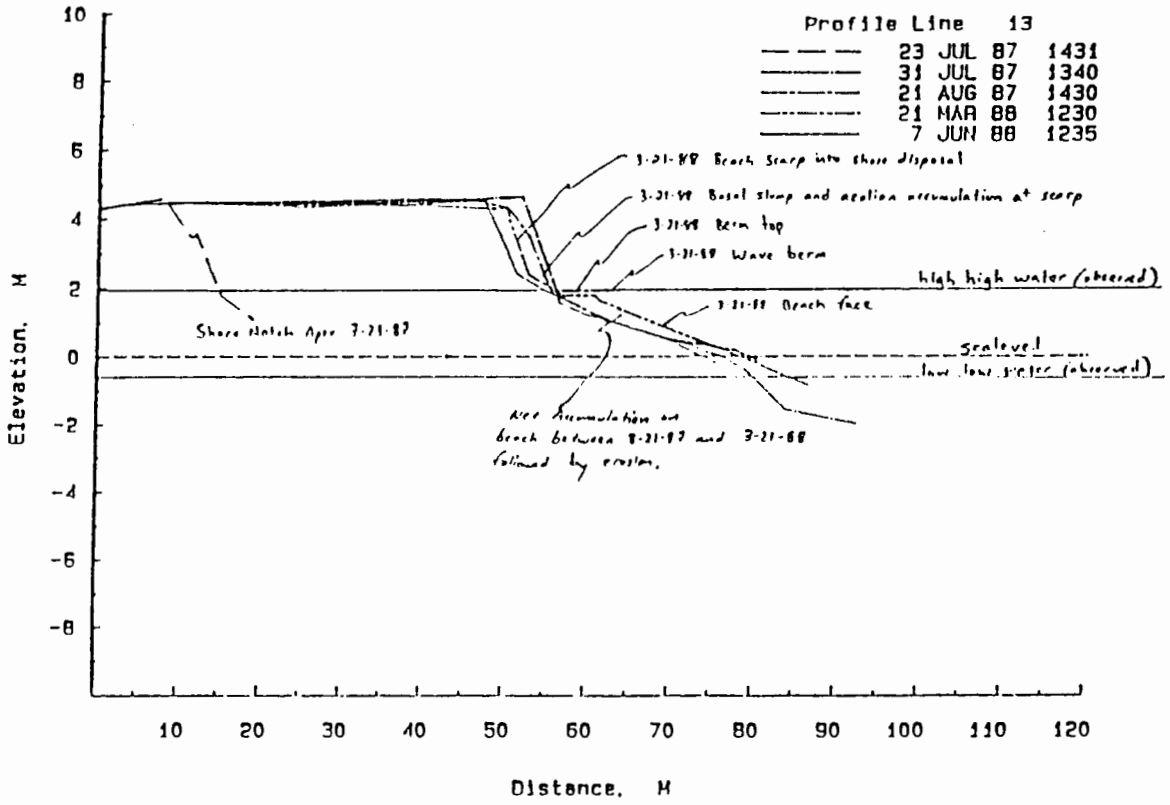


Figure 16. Shore profile changes over time. Puget Island site.

TABLE V

PROFILING ERROR

Profile	A (area, m^3)	$V=A-A_{mean}/A_{mean}$
1	124.9	0.0015
2	122.1	0.0241
3	126.2	0.0082
4	127.3	0.0175

$V_{mean} = 0.0128 = 1.28\%$
$V_{max} = 0.0241 = 2.41\%$
$V_{min} = 0.0015 = 0.15\%$

part of any sedimentary environment, and a direct factor in the behavior of energy delivered to the shore, in wave breaking, and in sediment transport (USACE, SPM, 1984; Bascom, 1951).

Error analysis was done on the level and rod method by surveying the same profile four times with two different combinations of surveyors. The area under each profile above a zero datum (NGVD=0) was calculated and each compared. Table V exhibits the error that was found in the method of surveying used in the study.

Limitations concerning interpretations of the data and analysis in this study are as follows:

A. The data was collected over a limited period that did not include large hydrologic events that are important in any hydrology study used to make long-term interpretations.

B. The data was collected at unequal time intervals which may have not been the best increment or descriptive enough for certain seasons. These are factors beyond the control and scope of this investigation.

C. An error exists in the data collection, an error that is analyzed and presented in this section. Interpretations are only valid then based on changes that occur outside the error range.

D. The processes acting on these slopes are described as observed in this study, but only some of these were quantified to any degree of integrating into a model or analytic solution descriptive of slope evolution and sediment transport.

F. The interpretations and derivations presented in this study are based on foundations presented in this thesis, with conclusions that must be viewed in this light. Conclusions present a scientific description based on the small amount of data representative of a complex system. Thus, analysis of data was integrated with the theoretical/laboratory work of others as much as possible to make realistic interpretations.

OBSERVATIONS OF BEACH CHARACTERISTICS

Geomorphology

Visual observations recorded with photographs and sketches provided qualitative descriptions of shore features that characterized the study site and its development. During profiling, specific shore features were recorded where they were found on the profile. Some geomorphic forms such as the distinct topographic wave created "shore notch" feature were also described by sampling the structure to define any distinct grain size differences.

A sediment grain exposed to a distinct hydraulic regime behaves according to its shape, size, and density. When a variety of grains of varying size, shape, and density are present, they each may have a different response to the same hydraulic regime. Distinct mineral banding and structures can result. A grain's behavior is also dependent on its relative size in comparison to the grains around it (Komar, 1987b). The cumulative grain response of a sediment population results in an assorted variety of distinct bedding structures. These structures can be described by their appearance, location on the shore slope, and by the hydraulic process which formed them. Structures were photographed or sketched, the probable process responsible for the structures' formation was noted, and their positions on the beach face were recorded.

SHIP PASSAGE

Background Conditions

The lower Columbia River has a complicated set of hydraulic actions occurring in its channels. Water motions are controlled by: freshwater discharge, tidal range, wind waves, ships and channel geometry. All these processes were observed, but impacts of ship waves in shallow water were examined with most detail. Thus, the simplest background conditions would occur when all other variables are neglected occurs when: the river current velocity, u =

0, the time of low and high water slack; and where and when wind effects are negligible. To establish background conditions, near shore surface velocities were taken and wind waves described.

The Ships

The Columbia River Pilots Association provided the following vessel descriptors; length over-all (LOA), beam or breadth extreme, and mean draft during passage. Draft or the submerged depth of a ship is influenced by the pitch of the vessel. Pitch is the rotation of the ship upon a horizontal axis that bisects the ship perpendicular to the ship's long axis, identical to a "rocking-horse". A high pitch would correspond to a high standard deviation about the ship's mean draft. It is assumed that the mean drafts obtained from the Pilots is representative of a ship with no pitch or a level keel. General ship descriptors such as dimensions and net displacements were obtained from the Lloyd's Ship Register (1987-88) and Jane's Fighting Ships (1987-88), such as dimensions and net displacements. The information acquired was inadequate to describe the hull geometries of the vessels quantitatively. This is a problem other studies have had (Sorensen and Weggel, 1984). It is assumed that draft and speed of the vessel will outweigh the other factors in the net effects upon the shore slopes. But the correlation of the ship factors with

actual impacts upon the shoreline and resulting sediment transport is complex. Much of the interpretation and conclusions of this study were drawn from analogy using established expressions and case studies presented in the literature (PIANC, 1987; Johnson, 1966; Ofuya, 1970; Sorensen, 1973; Sorensen and Weggel, 1984; Brebner and others, 1968; and others listed in references).

To describe a ship wave event a single low pressure transducer [transmetrics P21C 0-15 psi] was placed in water 1-2 meters of depth in proximity to the sampling array. The transducer was attached to a two channel strip chart recorder that recorded the signal. Each day sampling was done, the transducer was checked and calibrated by raising and lowering the transducer through the water column. The system usually worked well. Error estimation and calibration of the transducer-strip chart recording system was done to establish the precision of the method. The strip chart record was run at either eight or sixteen inches per minute, but the lower speed was found to create fewer problems in paper binding. The strip chart recorder was tested each day operated to establish the recorder's precision. Error is presented in Table VI.

SEDIMENT ANALYSIS

Sediment characteristics such as specific gravity, the average unit weight of the population, grain size and

TABLE VI

ERROR IN STRIP CHART RECORDER

Time Calibration

Strip-Chart Record	Minimum Error	Maximum Error	Mean Error
8 in./min (.13"/sec)	0.0%	3.0%	1.5%
16 in./min (.27"/sec)			
Transducer Depth			
Measurements	0.0%	13.0%	3.0%

shape affect the sediment population's behavior when exposed to a hydraulic regime.

Unit weights of the dry loose sand were obtained by splitting the sample, weighing the split and determining it's volume with graduated cylinder. The average grain density was obtained by weighing a dry sample and then finding the sample's volume by the displacement of water in a graduated cylinder.

Two methods were utilized in grain size analysis: mechanical sieving and settling tube analyses. Each method provides a very distinct analysis. Sieving, because it uses square openings, is also a measure of grain shape. A grain's intermediate diameter will govern whether or not it will pass through the sieve. Standard preparation of the samples was followed in the analysis of grain size (Blatt and others, 1980).

Mechanical sieving involved first wet sieving the 1-2 kg sample with a 325 mesh sieve to remove any silts and clays from the sample and then placed in an evaporating oven. Grains of silt size and finer account for less than 0.01% of the beach sand samples. The sample was then dry sieved using one, one-half, or quarter phi intervals. Wet sieving is a more precise technique when the population has a significant portion of fine sand and smaller particles. The water releases these surface tension tending to hold these very small particles together. When wet sieving was used, the sample fractions were then dried and weighed. Dry sieving was done with a roto-tap machine for 15-20 minutes. Each fraction was then removed and weighed.

The settling tube technique provided a more rapid and continuous recovery of the sample distribution of sediment falling velocities and approximate grain size distribution. To obtain a realistic presentation of the sediment's size distribution with the settling tube, a mechanically sieved sample at quarter phi intervals was used to calibrate the process. Each interval was run on the settling tube and the median settling time, t_{50}, plotted for each size fraction, as exhibited in Figure 17. Samples are first split to obtain a representative sample of approximately 2 grams. Calibration of sediment samples enables the settling tube system to rapidly give the user continuous data describing a sediment population. The logarithmic

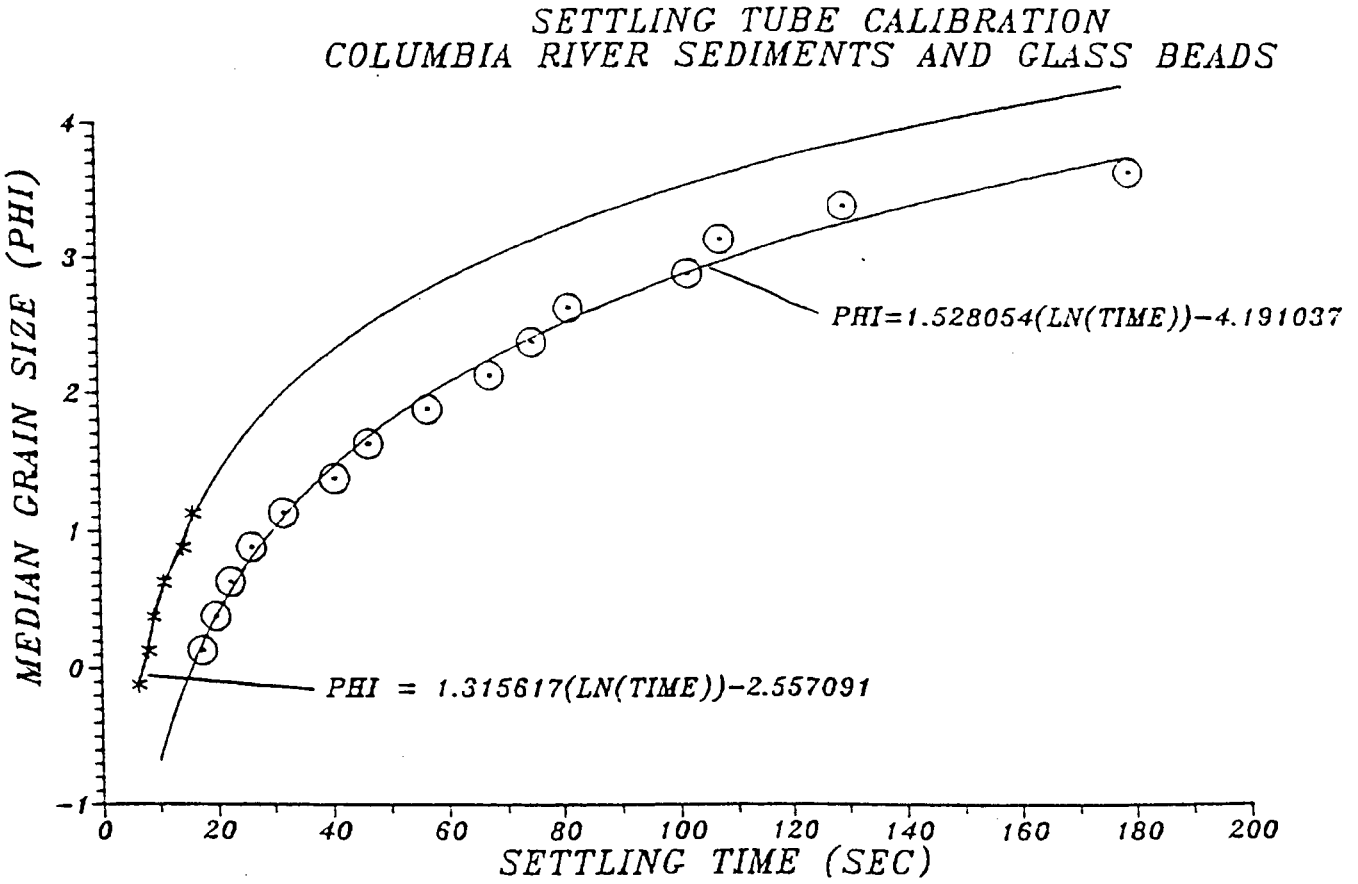


Figure 17. Calibration curves. Two mechanically sieved data sets. Stars represent glass beads (spheres) and the circles represent unreworked Puget Island dredge spoil sand, sampled in September 1987. Logarithmic curves were used to convert settling time from settling tube to an estimate of grain size, enabling grain size distribution acquisition from the settling tube system.

line of best fit was used to derive an equation converting settling time to size and the computer generated data file thus could include an approximate estimate of grain size. This data file was constructed with a BASIC program that used digital data converted from an analog signal. The analog signal is sent from the strain gage in the settling tube measuring the accumulation of sediment on a plate. The entire settling tube process is shown in Figure 18.

The interpretation of sediment size distributions has been of critical importance and debate in engineering and geologic disciplines since the early 1900's. Stochastic descriptions of a sediment population enable researchers to correlate sediment behaviors to specific in situ and sediment transport conditions that enables realistic interpretation of a sediment response. A statistical description of a sediment size population has become increasingly important in sediment transport theory (Einstein, 1972; Komar, 1987a, 1987b; Gomez and Church, 1989).

The most simple model of a sediment size distribution is the Gaussian or normal distribution. Statistical description of a sample based on graphical parameters (Folk and Ward, 1957) have been widely used in geological research and are applied in this study. Moment measures were also calculated for representative samples.

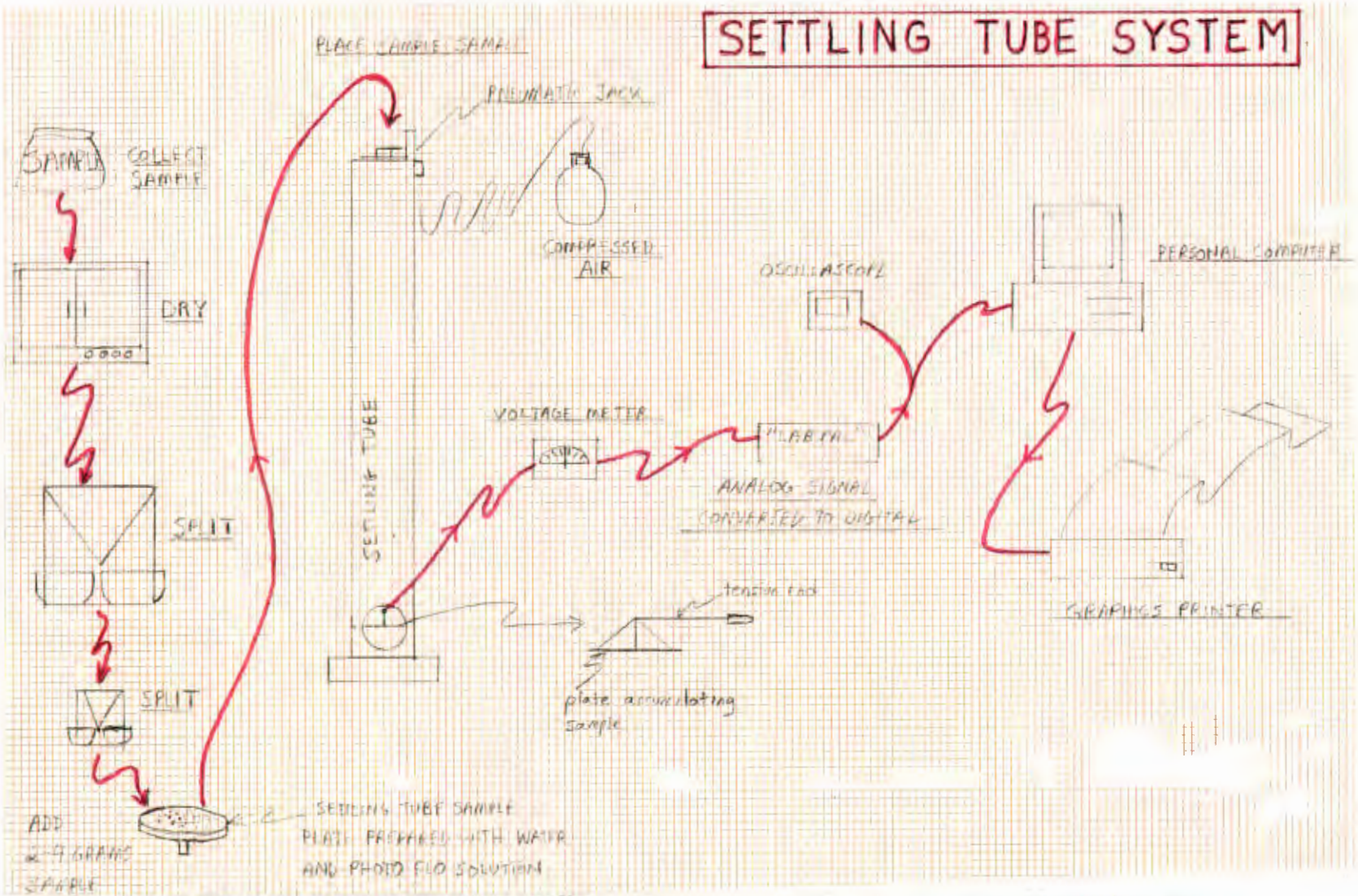


Figure 18. Settling tube. Cartoon of the two meter settling tube system in the PSU sediment laboratory.

SEDIMENT TRANSPORT

To evaluate the magnitude, direction, and rate of sediment transport across the beach face a field apparatus was needed that could collect sediments during a given event. The only systems found in the literature that were designed to meet similar criteria were used in the surf zone along the Japanese coast and along a North Carolina barrier beach (Katori, 1982; Katori, 1983) and (Kraus, 1987; Kraus and Dean, 1987b), respectively. These experiments presented an example of shallow water sampling in a surf zone. But because of constraints in economy, labor, and physical factors, a system had to be designed that would not only give a representative sample of longshore sediment transport as in the works of Katori and Kraus, but also give transport vectors on the beach face.

An effective method with minimal requirements for equipment and personnel was designed to document sand movement near the bed partially based on work by Hubbell and others (1986). Little such sampling has been done to date (Kraus, 1987). The design encompassed the following criteria: a minimum of hydraulic turbulence or interference; several sampling positions in the water column at the same lateral position; the potential to sample several transport directions; easily transportable; remain secure in desired position during most events; support sample bags of desired mesh for maximum flow; and

easy removal of sediment sampled. The trap mouths were made from square steel piping modified with a slightly flared exiting port, with an entry to exit ratio of 1:1.23, slightly less than the recommended 1:1.4 ratio for the Helley Smith bedload sampler (Hubbell and others, 1986). Design of the sampler set and array is presented in Figures 19 and 20, respectively. A nylon 105 micron mesh sieve cloth was used for the sample collection bags. The traps proved quite successful in collecting sediment put into motion during sampling events. Collected samplers are exhibited in Figure 21.

A low pressure transducer and strip chart recorder was used to numerically document the wave event during sampling. Other studies (Kraus, 1987; USACE, Portland District, 1986) video taped a staff gage(s) placed in the water near the sampling point or across the surf zone and then did spectral analysis, a labor intensive and costly procedure. The transducer offered a simpler method adequate for this study. When possible a video camera was used to record the event, providing verification and records of some of the events.

Problems with the sediment trap array system include stability during the turbulence of extreme events, (e.g. an out-going container ship the "Verrazano Bridge" caused a 1.52 meter drawdown and strong surge of approximately a meter that resulted in four of six trap array rods being

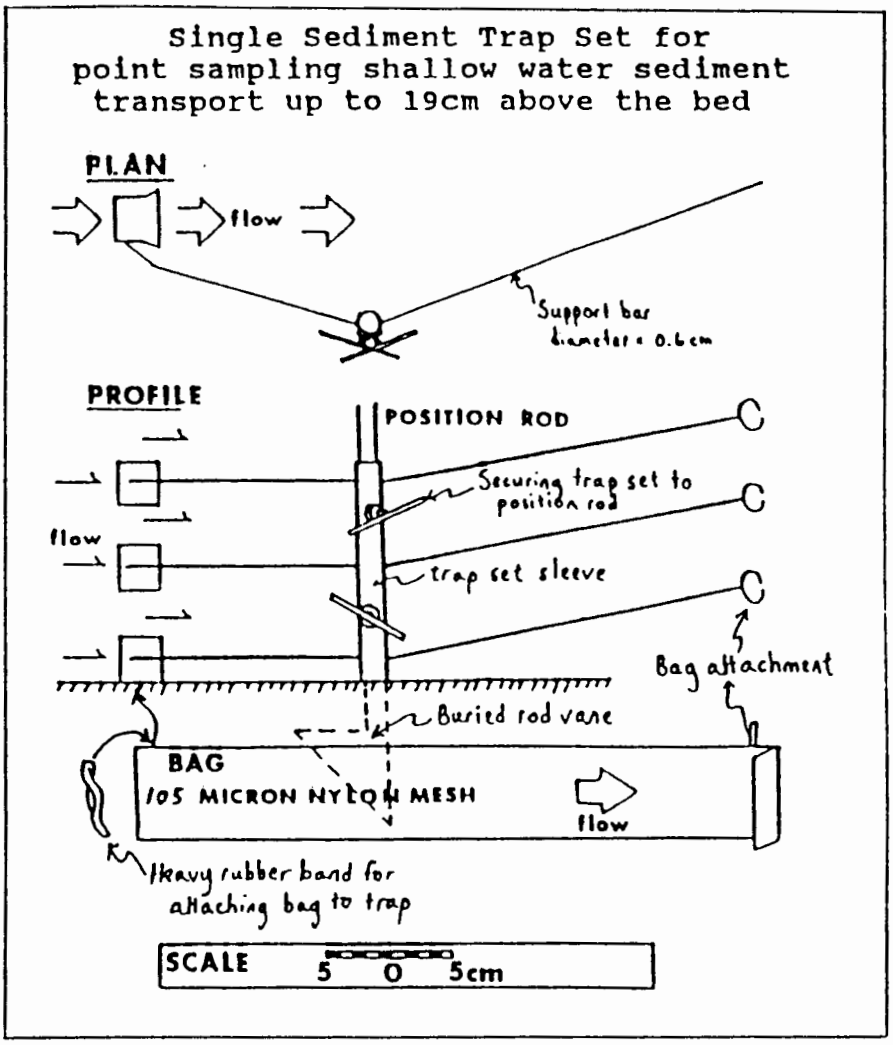


Figure 19. Shallow water sediment trap.

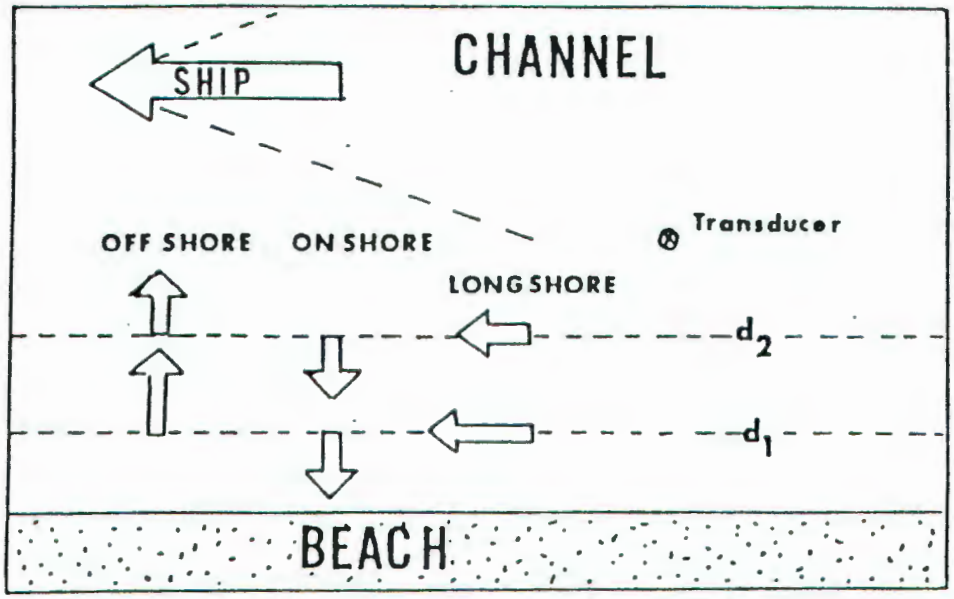


Figure 20. Sediment trap sampling array.

Figure 21. Removal of sand from sediment bag.

knocked over. Early problems with the arrays spinning on the vertical rod axis due to wave shear was remedied by welding a stabilizing steel plate to the bottom of the rod that is driven into the bed. To decrease the influence the traps themselves had on the hydraulics of the event, they were made small and the trap arrays were placed approximately three to five meters from one another. This introduces some error because interpretations are made using the entire array of several trap arrays covering a distance of up to eighteen m^2 along the shore to represent a point. This interpretation is valid if the shore geometry is relatively constant in the vicinity of the nearshore array.

RESULTS

THE STUDY SITES

Four beach sites were examined: Price Island, Washington, River Kilometer (RK) 55; Puget Island, Washington, River RK 62; Wallace Island, Oregon, RK 76.5; Gull Island, Oregon, RK 88. The principle study site was the northwestern tip of Puget Island, Washington, at 46°12'12" N 123°25'25" W. Figure 22 displays the location of the study sites. Each site is located adjacent to the navigation channel. Table VII lists the approximate distance from the mean water level line at each site to the center of the navigation channel.

Because the channel is maintained to a width of 183 meters, ninety-two meters can be subtracted from the distances given in Table VIII to give the minimum distance a ship will come to the shore. The average slope from shore to channel, assuming a channel depth of 13.7 m (45 ft.= advanced maintenance dredging, USACE 1989). The distance from the navigation channel to a site is critical in evaluating potential erosion. By design, the navigation channel approximately defines the river thalweg, thus is the region of highest current velocities and steepest side slopes. Ikeda (1982) showed that the side slope of a

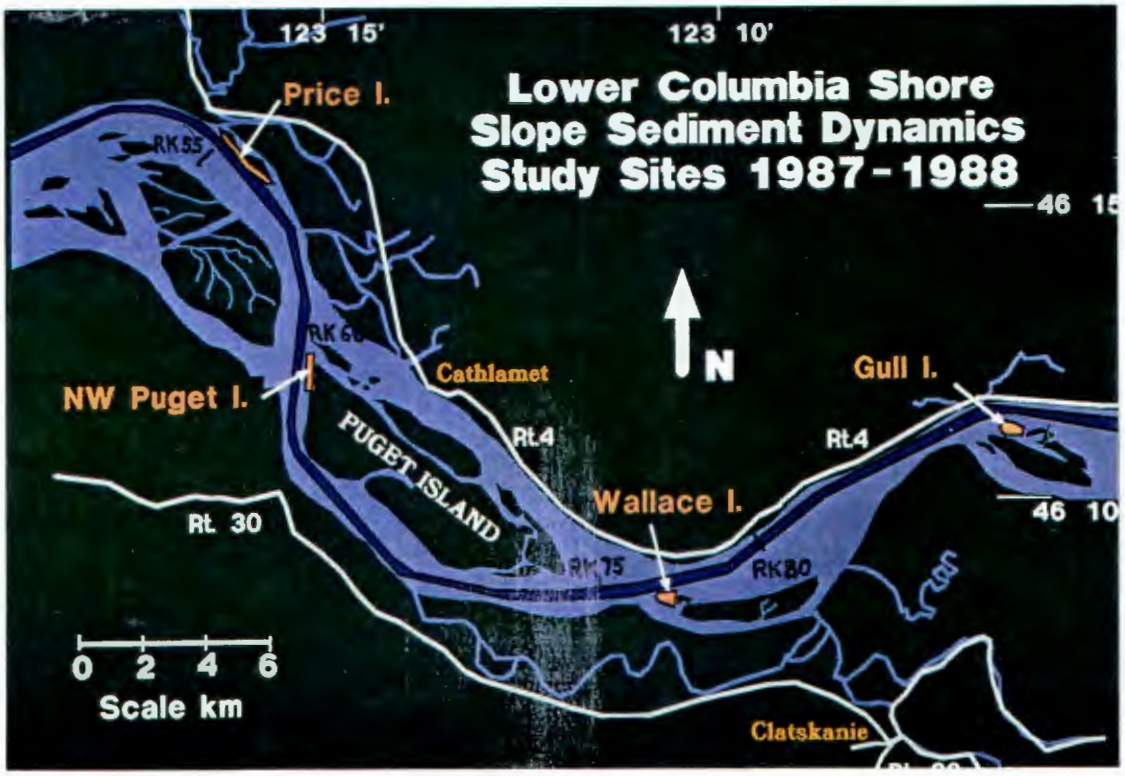


Figure 22. Sites observed in shore slope sediment dynamics study. Puget - RK WA-62; Price Island Site, RK WA-55.4; Wallace Island Site, RK OR-76.9; and Gull Island Site, RK OR-88.4.

TABLE VII

SITE LOCATION AND DISTANCE TO NAVIGATION CHANNEL

Site	RK	Distance to channel center line
Price	WA-55.4	215m (channel parallel to shoreline)
Puget	WA-62.3	270m (channel parallel to shoreline)
Wallace	OR-76.9	305m (channel parallel to shoreline)
Gull	OR-88.4	280-350m (channel oblique to shore)

TABLE VIII

AERIAL IMAGERY ANALYSIS OF EROSION 1939-1983

West bank of Price Island (square meters)
Cumulative Area

Year	Eroded	Years
1939	0.00	0
1948	60,299	9
1957	119,788	18
1961	130,310	22
1966	145,284	27
1968	163,090	29
1970	187,169	31
1973	204,570	34
1974	223,591	35
1978	250,301	39
1979	270,940	40
1983	329,620	44

channel can play an important role in lateral bedload transport leading to channel shoaling. Shore slope at depths less than one half of the deepwater wavelength of water waves controls wave refraction and reflection in transitional and shallow water (USACE, 1984) and thus the incidence and magnitude of ship waves (Johnson, 1968).

Price Island, Washington at RK 55.0 (River Mile, RM, 34.4) and Gull Island, Oregon at RK 87.8 (RM 54.9) were both profiled, observed, and sampled during 1987 and 1988;

no quantitative measurements of sediment transport were made. Visual observations of sedimentary structures, geomorphic features, and ship wave behavior were made at Wallace Island, Oregon at RK 76.5 (RM 47.8).

SHORE EROSION

Historic records of the study region offer information that more closely represents the "natural" conditions of the river than are observed today with the extensive modifications that have occurred in the last century by human development. These modifications include: shoreline levees, wetland drainage, beach nourishments, dredging, reservoir construction, and pile dike fields. Figure 23 presents a 1913 navigation chart of the Price Island and Puget Island study reach. The deepest water soundings (Figure 23) approximately trace the river's thalweg. Shallow water soundings delineate regions of natural shoaling, areas that have been utilized as sand disposal sites (USACE, 1989).

Figure 24 presents 1913 soundings in the vicinity of Gull Island (north of Grimms Island, Oregon). Gull Island was much smaller in 1913 than today as a result of continued sand disposal and a relatively low energy environment. Gull has traditionally been a site of deposition or shallow water sand bar. Price and Puget Island sites are land masses lying above mean highest high water.

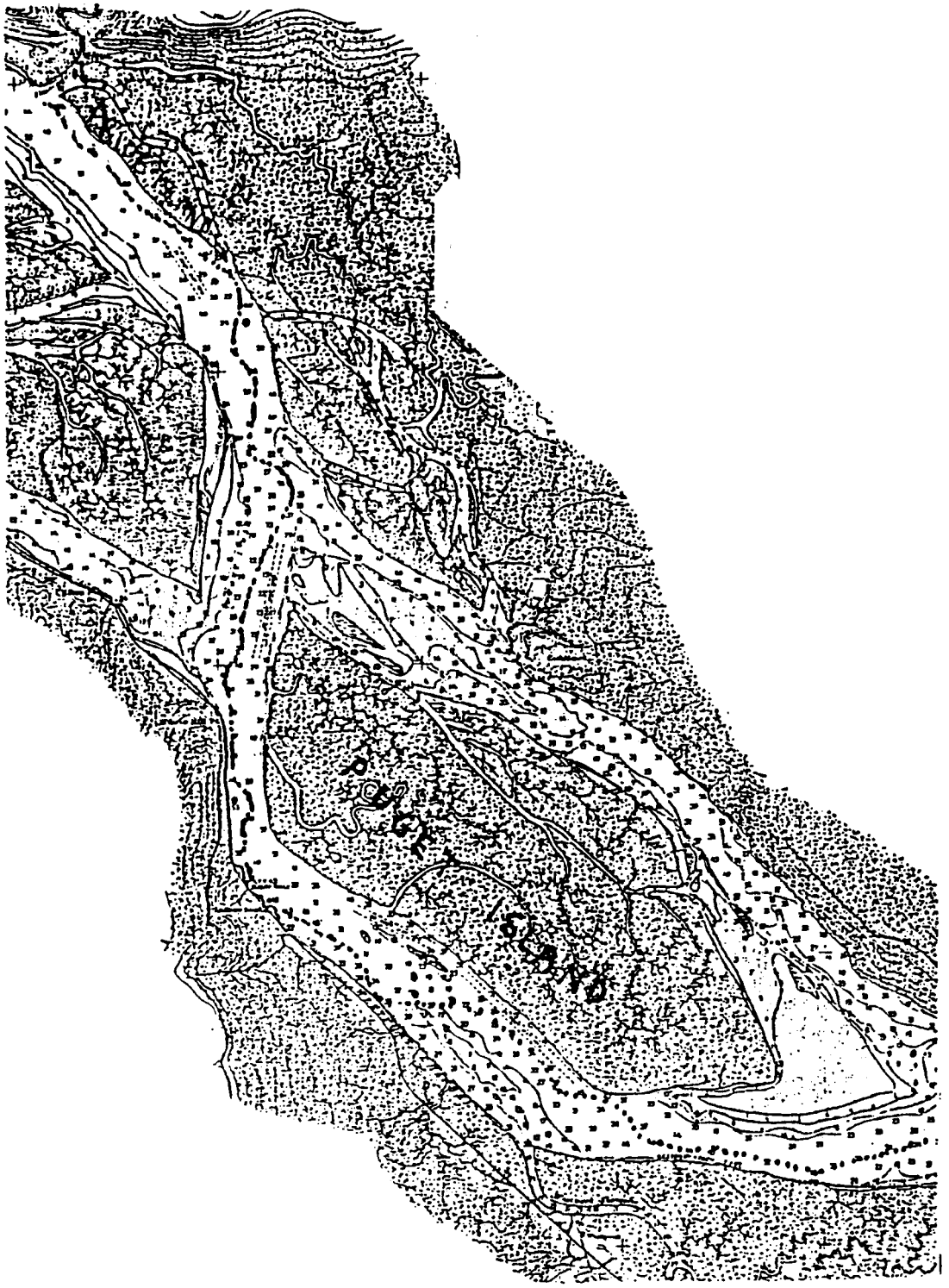


Figure 23. Columbia River soundings, 1913. Price Island and Puget Island reach (NOAA, 1913).

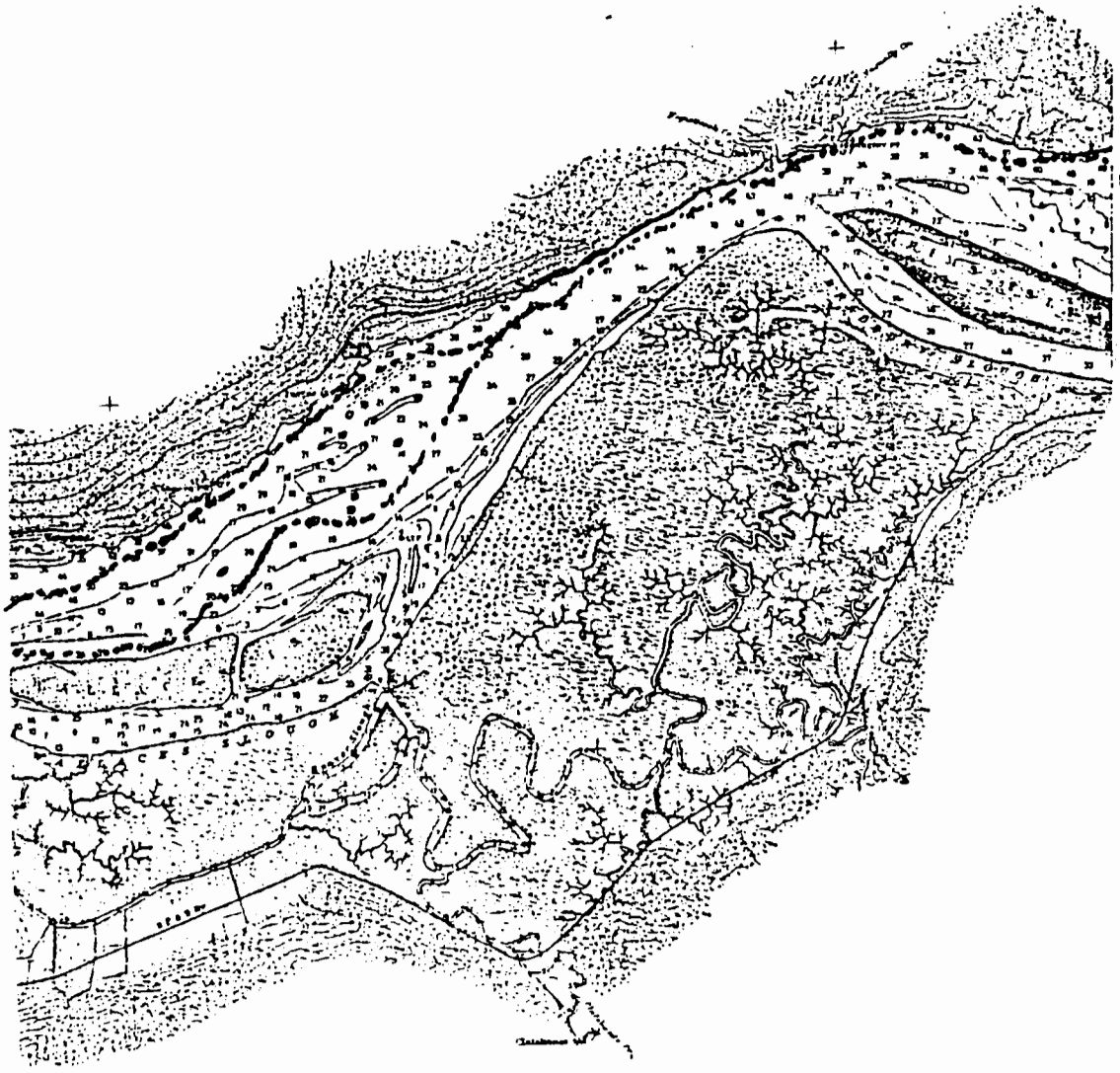


Figure 24. Columbia River soundings, 1913. Grimms and Gull Islands, Oregon (NOAA, 1913). Note Gull Island is primarily a shoal with a large shallow water intertidal region north of Crims Island. This region of shoaling is now mostly above mean highest high water due to continued site nourishment from dredging operations.

Aerial Image Analysis, Price Island

7,204,800 m^3 (9,423,000 yd^3) of sand was dredged from the Skamokawa reach of the lower Columbia between 1906 and 1986 (USACE, 1988b). To dispose a portion of this sand, beach nourishments have been made since 1959 on the southwest side of at Price Island. The site lies adjacent to the navigation channel as illustrated in location map in Figure 22. Erosion along Price Island was evaluated using aerial imagery and survey profiling (Abbe, 1988a). The beach nourishments may have slowed erosion on the southwest flank of the island, a factor that should be considered in evaluating aerial imagery with respect to time.

Aerial imagery at a scale of 1:11,111 was stereoscopically analyzed by Abbe (1988a) to determine shoreline changes from the 1939 to 1983. The changes in the Island's area have been dramatic, with a loss of approximately 330,000 m^2. Figure 25 presents an overlay of the cumulative changes at Price Island between 1939 and 1983, clearly showing extensive erosion in this period. Erosion plotted as a function of time is exhibited in Figure 26, portraying the rate loss of material in the resultant curve. Table VIII presents areal differences computed from the aerial image analysis.

Aerial Image Analysis, Puget Island

The Puget Island site was examined only for long-term changes with aerial imagery. Because of extensive historic

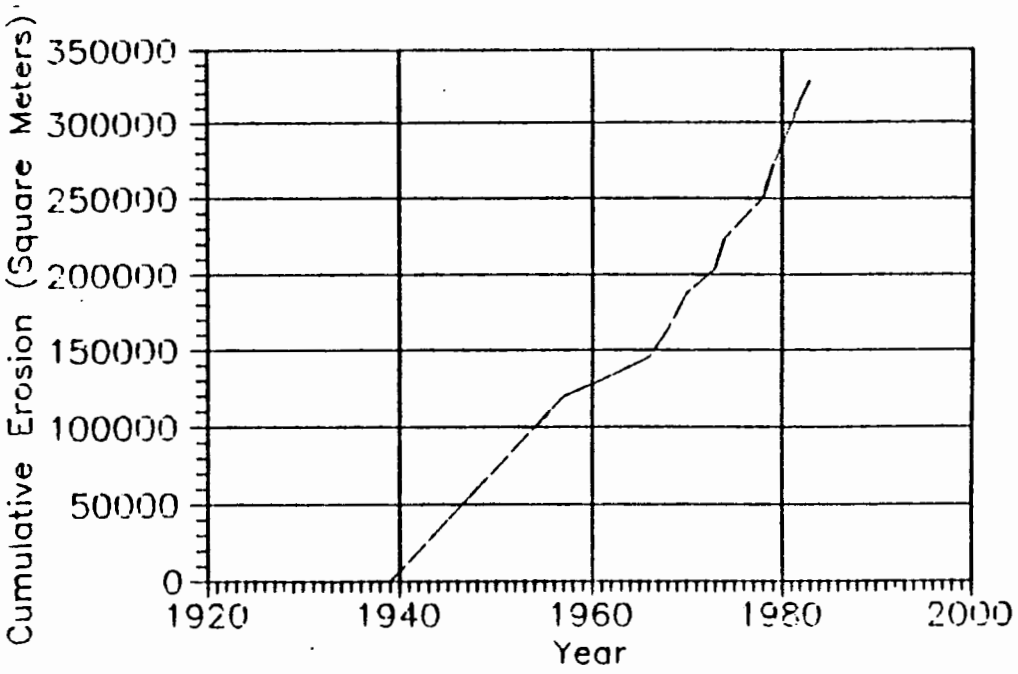


Figure 25. Price Island erosion. West flank of Price Island from 1939-1983.

sand disposal, changes have not been as dramatic as at the Price Island site WA-34. Figures 27 and 28 are computer generated images from the aerial photographs that summarize changes at the Puget Island Site between 1939 and 1983. The Puget site has had a net loss even with constant nourishment of sand by dredged sand disposal (USACE, 1988b).

Using the computer images digitized from aerial photographs, estimates of erosion and accretion at the northwest end of Puget Island were made. Between 1939 and 1983 approximately 56,795 m^2 of shore has eroded from the island adjacent to the navigation channel, immediately north of the Puget site. No shore nourishments or sand disposals had been placed at this location directly north

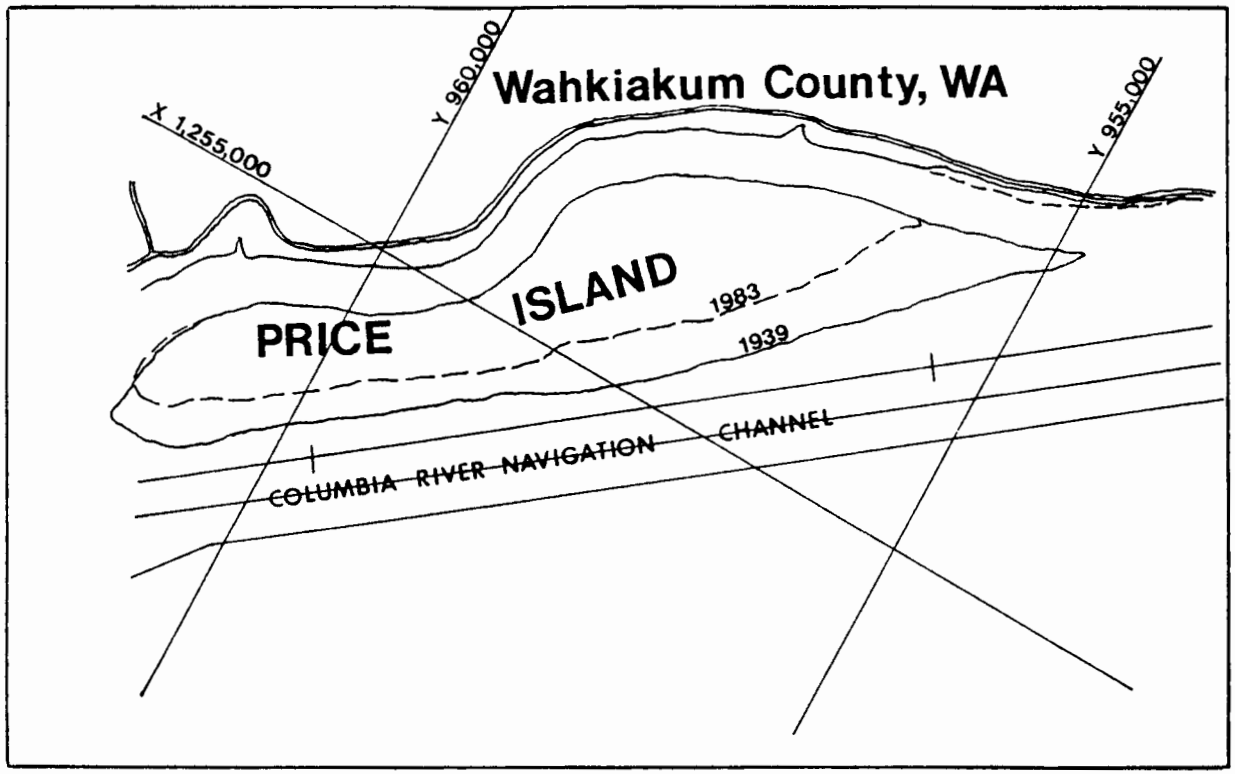


Figure 26. Changes at Price Island. Change along Price Island's western flank during the period from 1939 to 1983. The central portion of the Island's west bank has received sand nourishment since 1959.

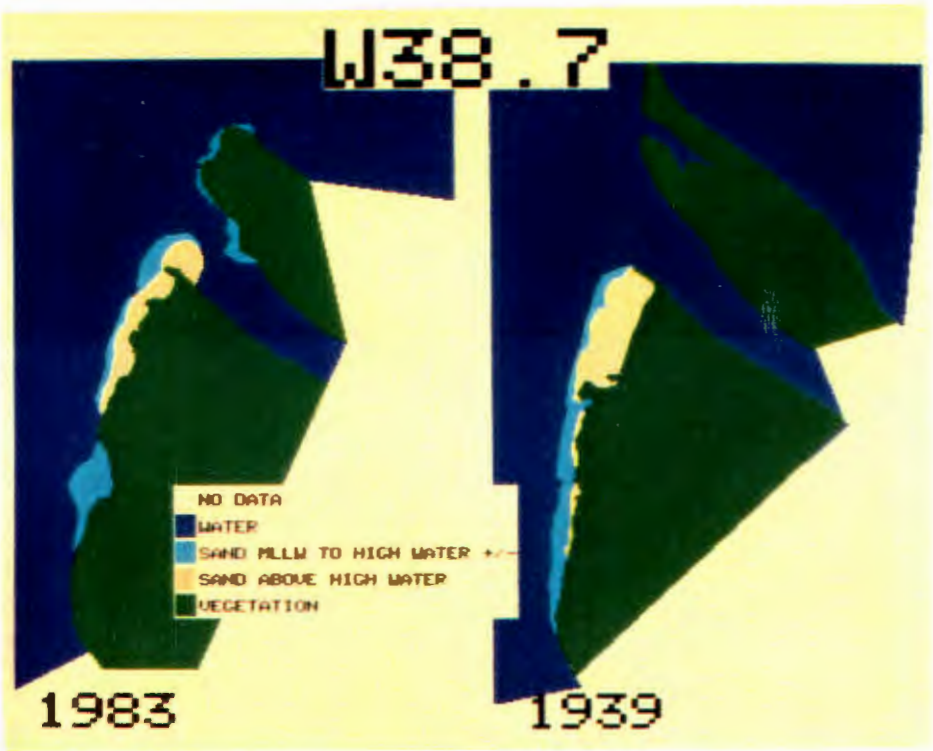


Figure 27. Computer imagery of Puget Island site. Based on aerial photographs, 1939-1983. Note erosion of small island north of Puget site.

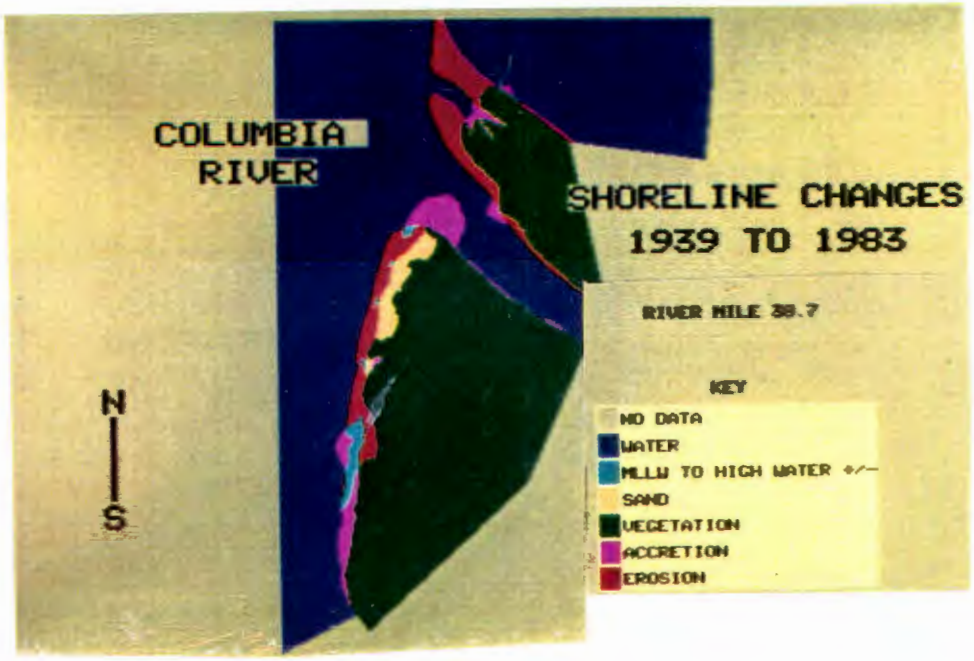


Figure 28. Computer imagery of Puget Island site. Digitized from aerial photographs, 1939-1983. Net erosion evident even though site has received a minimum of two million cubic yards (1.5×10^6 m^3) of sand during this period.

of the Puget site and it offers a suggestion of possible erosion at the Puget site had not extensive shore nourishments been made. A minimum estimate of the volume of sand contained in the accreting lobe north of the Puget site with a 1.0 meter accumulation, as interpreted by the difference between present topography and the 1913 soundings produces a volume of 33,528 m^3 of sand. The average accretion would be 761 m^3 per year. The source of this sediment has been the continued disposal of sand at the Puget site. The volume of sand nourished at the Puget Island site during the same period 1939-1983 far exceeds the minimum estimated mass stored in the accretionary lobe. During only the fifteen year period from 1968-1983 1,450,000 m^3 (1,897,000 yd^3) of sand was disposed at the Puget site (USACE, Portland District, 1988b). The evidence of net erosion at the site even with sand disposal and storage estimates in the accretionary lobe suggest that a considerable portion of this sediment is transported completely out of the local shallow water region encompassing the Puget disposal site.

Aerial Image Analysis, Gull Island

The Gull Island site (46°11'15"N 123°09'00"W) was examined for long-term changes with aerial imagery. Figure 29 is a computer imagery based on aerial photographs of the cumulative changes at Gull Island between 1939 and 1983, exhibiting net aggradation of the site. Gull Island is

Figure 29. Computer imagery of the Gull Island Site. Digitized from aerial photographs, 1939-1983. Gull is the small island lying northwest of Crims Island.

north of Crims Island. Figure 29 shows the development of Gull Island from a shallow water bar to a well developed Island, the result of continued shore disposals of dredged sand from 1939 to the present.

Shore Profiles, Price Island

The shore slope of a river is defined as the region from the levee crest to 2 meters below the level of lowest low water. The river shore slope is an ever changing-responding geomorphic feature. Describing a shoreline as a function of time is an important part of many coastal studies done to establish volume changes and slope development. During periods of prolonged "steady-state" conditions shore slopes may display a stable form in "equilibrium" with the acting processes. But if this slope is exposed to a new set of processes or change in magnitude of existing processes, the shore will adjust to suit changing conditions. Processes include wind, currents, waves, and dredging.

Profiles compiled for Price Island (RK 54) during 1987 and 1988 show distinct erosion. Figure 30 presents the four profile lines used at the Price Island site.

Using profiles, a cumulative estimate of sand lost in the Price Island grid (Figure 30) is presented in Table IX.

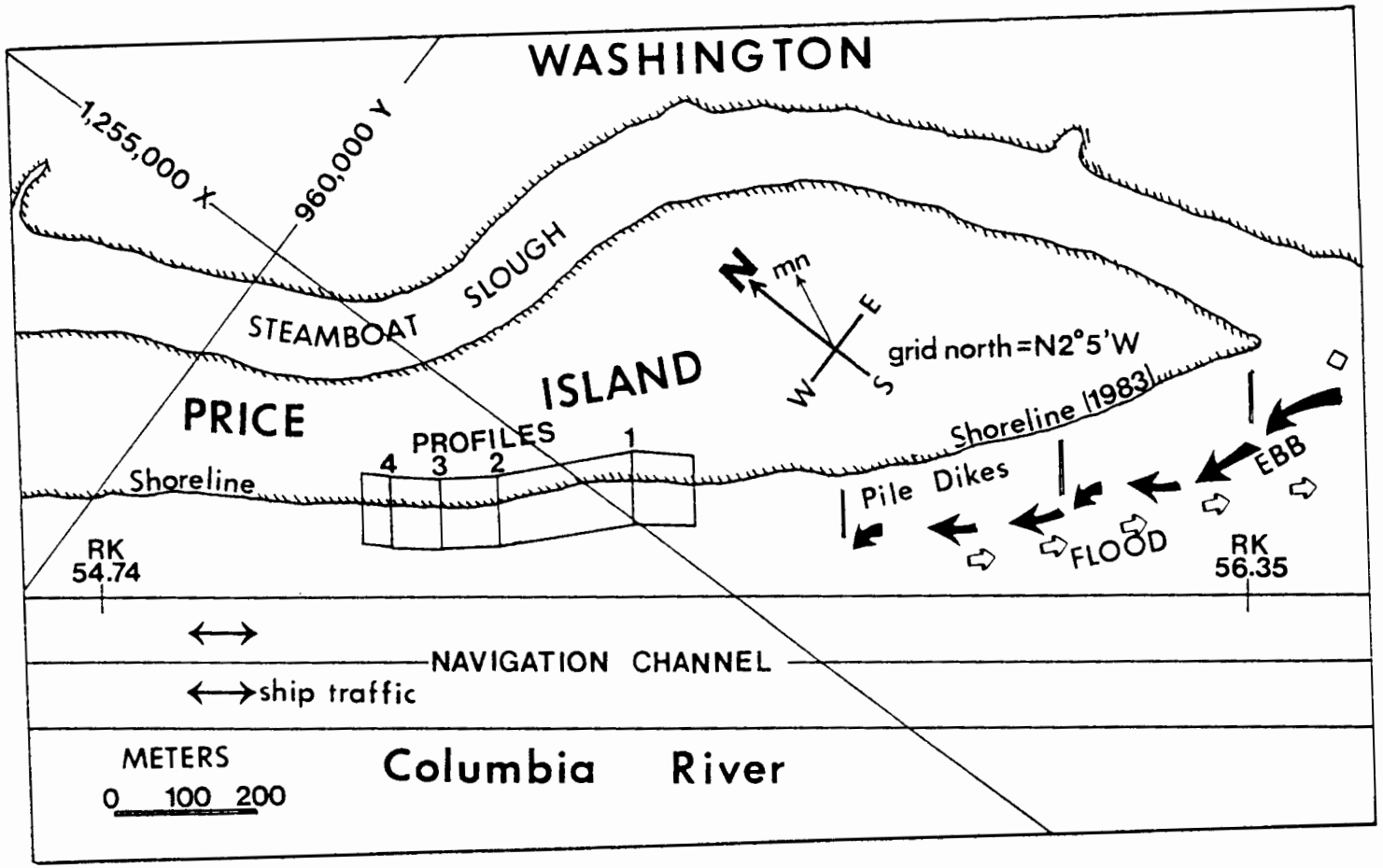


Figure 30. Price Island site profile grid.

TABLE IX

CHANGES IN VOLUME AT THE PRICE ISLAND SITE

Between June 15, 1987 and June 29, 1988

Profile	Cell width(m)	Cell Volume Change (m^3)	Relative Cell Change m^3/m
1	157	- 4,370	- 27.8
2	135	-11,718	- 86.8
3	76	- 4,720	- 62.1
4	52	- 6,920	-133.1

Total Estimate -27,729
Total nourishment June 1-10, 1987 = 178,687m^3
Estimated loss = 15.5%
$Error_{max}$ = +/- 631m^3

Shore Profiles, Puget Island

The twenty-one profile lines surveyed at the Puget Island site (RK 62) were used to document slope changes and calculate volume changes over time at the site. Figure 31 presents a plan view of the Puget site monitoring layout.

Twice during the study period the Puget Island Site was nourished twice during 1987-1988 with channel dredged sands of the adjacent Puget Island Reach Channel. Between the 24th and 29th of July, 1987 approximately 97,903 cubic meters (128,045 yd^3) of sand were placed at the site. Between the 30th of July and 6th of August in 1988 196,738 cubic meters (257,308 yd^3) were laid down at the Puget site (USACE, 1988c). The dramatic changes a site undergoes after receiving a beach nourishment are illustrated in

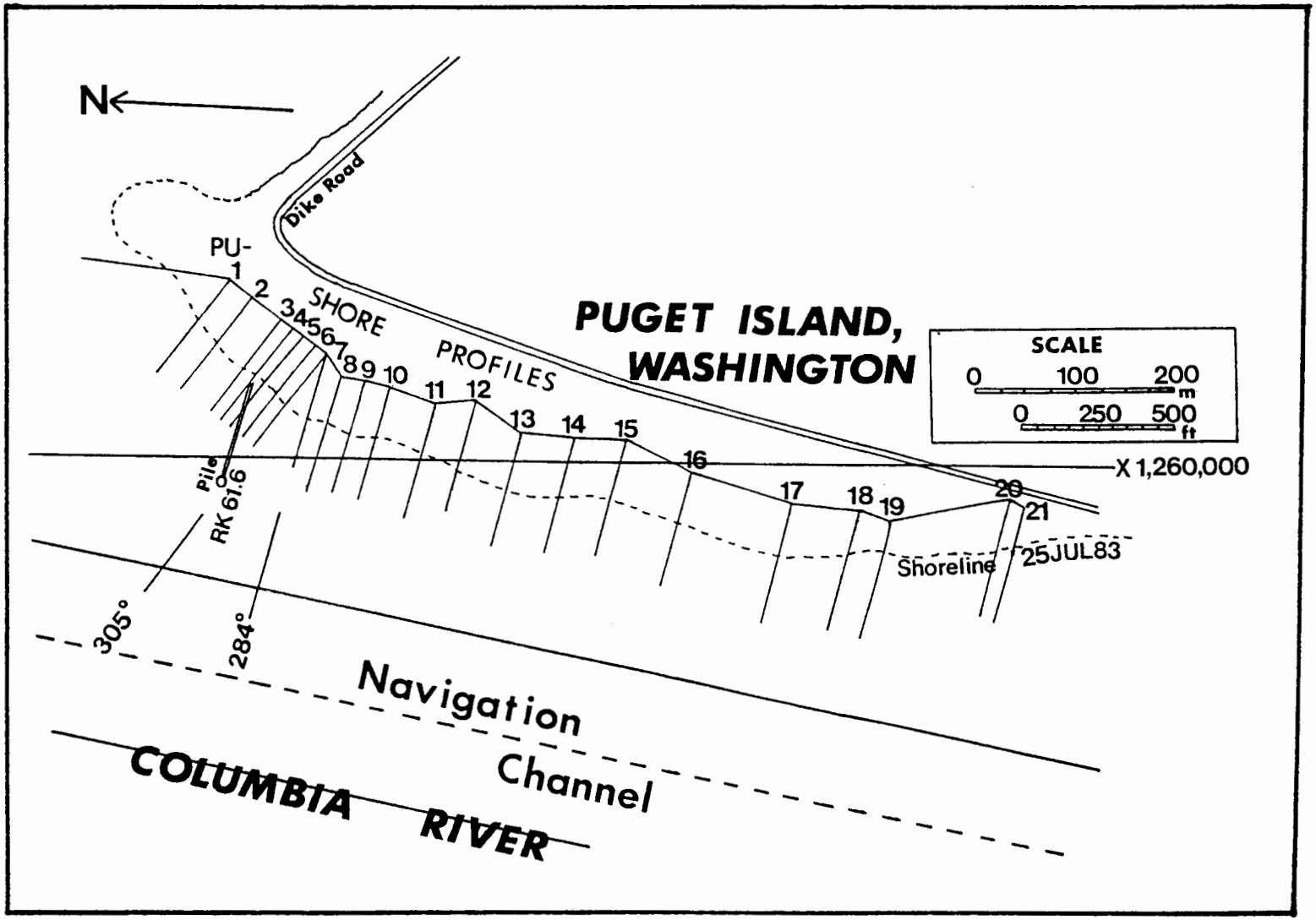


Figure 31. Puget Island profile grid.

Figures 32 and 33 which exhibit before and after views of the Puget site for the July 1987 nourishment.

Table X exhibits the computed volumes of sand eroded or deposited on the profiled beach slopes at the Puget Island site over about eleven months. After the 1987 nourishment at the Puget site through the period of July 31, 1987 to June 7, 1988 the estimated loss of sand from the Puget Island site was 26,197 m^3, about twenty-seven percent of the 97,903 m^3 quantity placed at the site during the July 24-29, 1987 nourishment. The eroded volume is equivalent to a daily flux out of the Puget site cell grid of about 72 m^3/day.

Slope development of the beach is illustrated in profile development with time, as displayed in Figure 34 (profiles in Appendix 1). Profile PU-7 had a slope of 1:55 or 1.0° on June 23, 1987 prior to the July 1987 nourishment. This slope is probably approaching an equilibrium slope angle for the Puget site with time (under the mean wave and current regimes during the slope development). After nourishment, on July 31, 1987 the beach face had a greatly exaggerated slope of 1:7.14 or 8°. By August 21, 1987 the beach face slope was 1:12.7 or 4.5°. Shore slope development is presented in Table XI. The upper beach is eroded and sand is deposited on the lower beach, typical of a low energy wave regime (USACE, 1984). If the water level reaches a two meter elevation it can be

Figure 32. Puget site before sand disposal. Looking north, from profile line 13. Photo: 23JUL87.

Figure 33. Puget site after sand disposal. Looking from about same site as in 32. Site was nourished with 97,903 m^3 of sand between July 24 to 29, 1987. Use trees at right for reference. Photo: 16SEPT87.

TABLE X

CHANGES IN VOLUME AT THE PUGET ISLAND SITE

Between July 31, 1987 and June 7, 1988

Profile	Cell width(m)	Cell Volume Change (m^3)	Relative Cell Change m^3/m
3	44	-4,812	-109.4
5	29	-5,035	-173.6
7	31	-4,702	-151.7
8	26	-3,148	-121.1
9	24	-1,577	- 65.7
10	38	-2,065	- 54.3
11	38	- 527	- 13.9
12	41	-1,015	- 24.8
13	53	- 356	- 6.7
14	53	- 975	- 18.4
15	62	- 560	- 9.0
16	88	+1,871	+ 21.3
17	87	- 830	- 9.5
18	49	- 462	- 9.4
19	76	-2,003	- 26.4

Total Estimate = $-26,197m^3$
Total nourishment July 24-29, 1987 = $97,903m^3$
Estimated loss = 27.0%

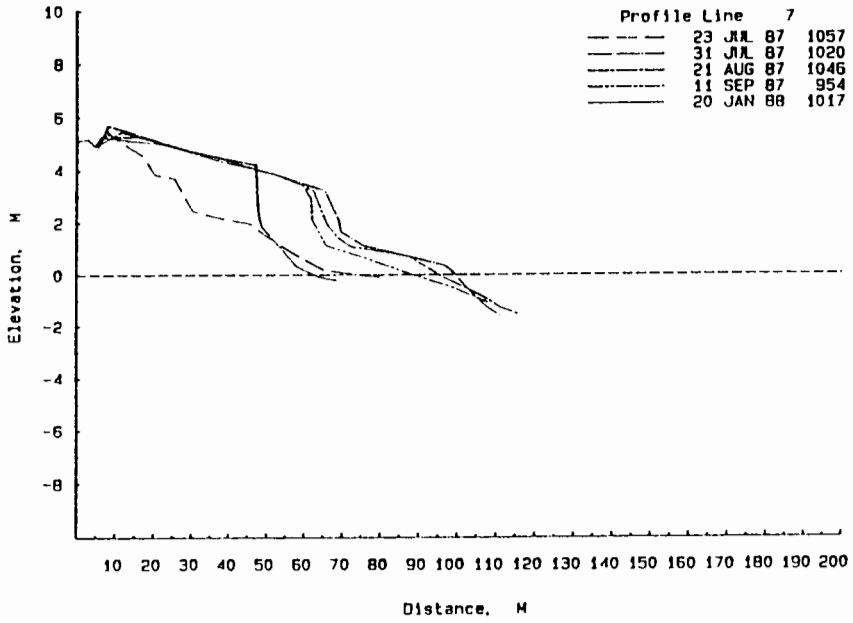


Figure 34. Puget Island site profile 7. Showing shoreline retreat. 23JUL87 before nourishment, 31JUL87 after nourishment.

TABLE XI

EXAMPLE OF BEACH FACE SLOPE

Development at Puget Site Profile No.7

Date	Location	Slope	Notes
07-23-87	Lower Beach	0.02	preceding nourishment
07-31-87	Lower Beach	0.14	directly after nourishment
08-21-87	Lower Beach	0.10	
01-20-88	Lower Beach	0.03	

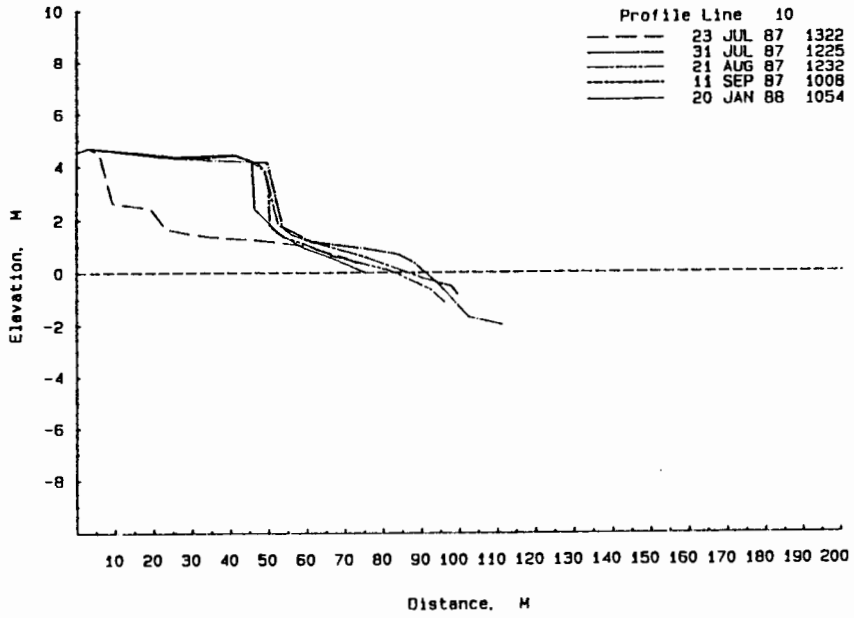


Figure 35. Puget Island site profile 10. Showing shoreline retreat and slope development.

expected that the beach slope will develop as a function of water actions (such as ship waves) up to that point. Extrapolating the "equilibrium slope" riverward from the high water level can yield an estimate of what sand that may be eventually lost to erosion. An example of shore slope steepening is seen in Figure 35, where the June 7, 1988 upper beach face is distinctly steeper than the January 20, 1988 upper beach face slope, the result of a shore notch.

Shore Profiles, Gull Island

The Gull Island site profile grid is presented in Figure 36. Gull Island was nourished with approximately 151,192 m^3 (197,740 yd^3) between July 29 to August 1, 1987.

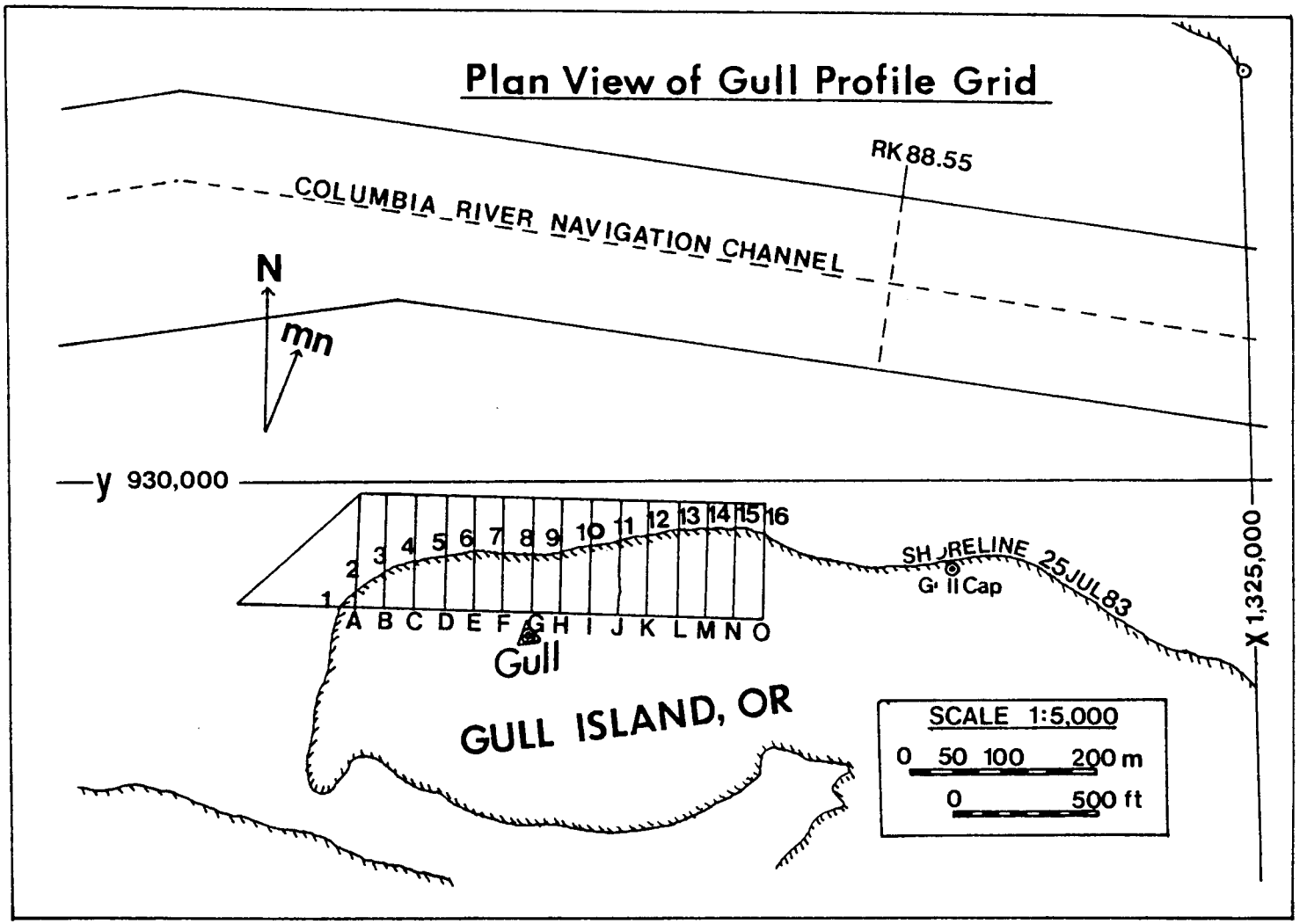


Figure 36. Gull Island site profile grid.

Figure 37 shows the Gull site before nourishment and Figure 38 shows it after the 1987 shore nourishment. Results from profiling at Gull Island suggest it is a relatively stable site, showing the least change of the sites examined. Table XXII presents the results of profiling at the Gull Island site.

OBSERVATIONS OF BEACH CHARACTER

Geomorphic Features

Geomorphic observations (Bekendam and others, 1988) can provide strong analogous evidence suggesting the dominant processes in bank erosion. The lower Rhine River has a bank morphology that has been directly impacted by the actions of ship waves (Bekendam and others, 1988), a bank that is similar in composition and morphology to banks of the lower Columbia (USACE, 1960; USACE, 1986; Abbe, 1989).

Figure 39 displays a "native" (natural) Columbia River bankline of silty clay, and exhibits a distinct wave terrace. Silty clay deposits constitute the native lower Columbia banks and a major Holocene Columbia River deposit occurring since the Wisconsin ice age. Much of the lower Columbia's native clay banks have been buried under sandy shore nourishments (USACE, 1988b). Figure 40 is a descriptive diagram illustrating geomorphology on channel and slough side of a "native" clay lower Columbia River

Figure 37. Gull Island site before sand disposal. Looking east from west end. Note abundant vegetation colonizing the upper beach face and no beach scarps, evidence of a stable shore. Photo: 28JUN87.

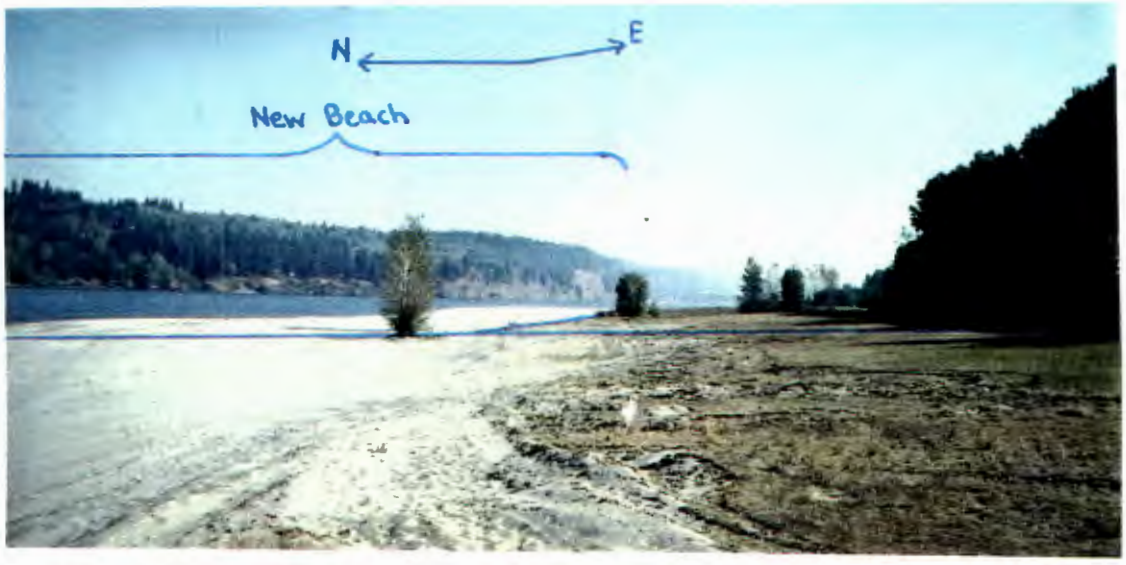


Figure 38. Gull Island site after sand disposal. View from approximately 60 meters behind Figure 37 photo. Photo taken 08AUG87.

Figure 39. Representative silt-clay bank bordering the lower Columbia River channel. Note the distinct wave cut terrace, debris, and eroding character.

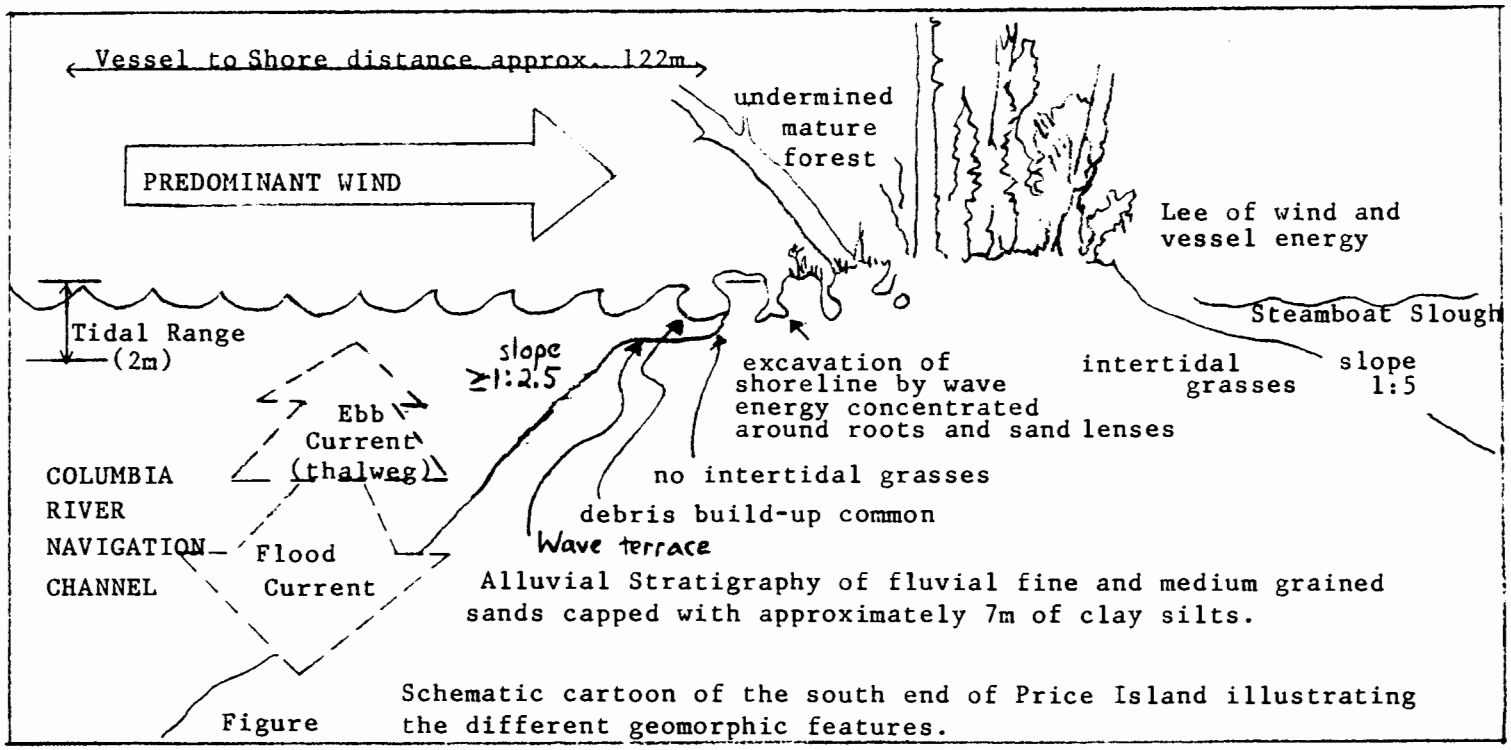


Figure 40. Price Island bankline erosion.

TABLE XII

CHANGES IN VOLUME AT THE GULL ISLAND SITE BETWEEN JULY 31, 1987 AND JUNE 7, 1988

Estimated Using Profile lines and unit cells

Profile	Cell width(m)	Cell Volume Change (m^3)	Relative Cell Change m^3/m
2	15.2	- 368	-24.0
3	30.5	- 234	- 7.7
4	30.5	- 341	-11.2
5	30.5	- 113	- 3.7
6	30.5	+ 656	+21.5
7	30.5	- 207	- 6.8
8	30.5	- 55	- 1.8
9	30.5	-1128	-37.0
10	30.5	+ 235	+ 7.7
11	30.5	- 241	- 7.9
12	30.5	- 12	- 0.4
13	30.5	- 85	- 2.8
14	30.5	+ 43	+ 1.4
15	30.5	-1357	-44.5
16	30.5	-1067	-35.0
TOTAL ESTIMATE	-4,266		

Total nourishment July 29 - August 1, 1987 = 151,192 m^3
Estimated loss = 3.0%

bankline, using the southeast end of Price Island at the present time as a model. The bankline on the channel side displays distinctive erosion, while the slough side lacks erosive characteristics. Several points along the Puget Island site prior to the 1987 nourishment exhibited severe erosion, as presented in Figures 41 and 42.

Constructing a Shore Nourishment

The method in which a sand shore nourishment is emplaced on a beach plays an important factor in the subsequent beach dynamics. Two distinct methods are employed to deposit channel dredged sand to nourishment sites.

The first method is an unrestricted slurry or hyperconcentrated discharge, that is directed across a shore. The sediment settles out when it reaches the river's edge. This technique builds locally large beach lobes with gentle slopes, but a considerable quantity of sand re-enters the river at points controlled by the water elevation during disposal. The majority of that sand settles out soon after re-entry into the relatively calm nearshore water.

The second method is called "beach diking," a technique in which bulldozers work steadily to maintain and direct the hyperconcentrated flow (slurry) with a sand dike riverward of the outflow. Figure 43 displays this commonly used method. The sand diking enables the dredge crew to

Figure 41. Shoreline near high tide at the south end of the Puget Island site. This shore is eroding despite an extensive vegetated cover, 08/87.

Figure 42. Apex of shore notch at Puget Island study site, July 23, 1987. Located at profile PU13. Vegetative cover slows, but does halt erosion.

Figure 43. Pipeline dredging operation. Shore nourishment at Puget Island site.

cover much more shoreline using the same quantity of sand and less time using unrestricted slurry discharge. This technique creates a steep, large berm near the water's edge, producing an unstable beach.

Because of the significant tidal variation, constructed beaches can result in a sinuous configuration when viewed from above (plan view), with the water surface controlling the location and slope riverward of the constructed sand dike or berm. The sinuous pattern results because the constructed dike follows the water-shore interface, thus during the tidal cycle the dike moves up and down the pre-existing shore slope (while migrating alongshore). A straight diked beach can be best constructed by constructing the dike at or above the high water contour to occur during the disposal. This beach configuration will control wave incidence on the beach by the refraction of waves approaching a site. Thus sediment transport by waves will be directly affected because of significant variations in longshore currents. If the sand dike were built above high high water, this beach would probably be very stable unless exposed to extreme flood conditions. But usually the dikes are built at or near the water surface. In both methods of shore nourishment the disposal pile is usually leveled off with bulldozers after the pumping has ceased. These two different beach nourishment techniques are clearly delineated in profiles

taken after the nourishment: low beach face slopes for the slurry method and a steep beach scarp near the water with the diking method.

Shore Slope Morphology

Several such characteristic coastal features which have been observed and presented in publications (USACE, 1984; Komar, 1976; King, 1972) were found along the shore nourishment beaches of the lower Columbia River. All of the features listed in Table IV are observed along the beaches of the study sites. Examples of beaches with many shore features along the same profile are displayed in Figures 44 and 45, at Wallace Island and Puget Island, respectively.

The shore or bankline profile characteristic of lower Columbia shore nourishments has a set of features, described in Table XIII from shore to river. The sedimentary features present on a shore slope reflect the sediment response to physical processes. Wave actions cut beach scarps and berms. Ship surge cuts beach scarps and carries sediment in the direction of ship motion, constructing accretionary lobes on the lower beach face. Wind generated waves deposit bands of heavy minerals above the high water berm and construct oscillatory ripples on the beach face. Tidal recession of the water surface will behead and sometimes destory ripples. Ship waves

Figure 44. Beach face on Wallace Island, Oregon. Northwest end of site, looking due east. Note small scarp at right and heavy mineral accumulation along upper beach swash zone. Inclined slope of nourishment pile to far right suggests it has been above highest water (no vertical scarps). Photo: 24JUN88.

Figure 45. Beach face at Puget Island site, looking north from profile 12. Note scarp at far right, suggesting entire beach face is active. Pumice in center is accumulated by

TABLE XIII

DESCRIPTIVE TRANSECT NORMAL TO SHORE SLOPE

Shore Slope Position	Feature(s)
Upper beach	Level (supratidal zone) topography, vegetation, and aeolian dunes Upper Beach Scarp Largest aeolian dune, directly above and shoreward of beach scarp
Beach Scarp Face	Vertical incision into the shore profile Beach Scarp Toe Set of collescing fans ("micro-bajadas"), steep inclined slope, wave cut berm Upper Beach Face Debris zone from wave swash, wave cut berm, heavy mineral banding, slope less than scarp toe, but steeper than beach face
Beach Face	gentle to moderate slope (1-5°), pumice banding, symmetrical oscillatory ripples with flattened crests and pumice in troughs, planar, smooth sand surfaces. Lower Beach Face Limit of lowest low water elevation, small (2-12cm) berm constructed and maintained by wind generated water waves, oscillatory

TABLE XIII

DESCRIPTIVE TRANSECT NORMAL TO SHORE SLOPE
(continued)

Shore Slope Position	Feature(s)
	ripples in shallow water (.1-1.5m), steepening of slope directly off shore.
Subtidal region	transition from oscillatory ripples parallel to shore to asymmetrical current ripples normal to shore (>1m depths), steepening of slope.

obliterate ripples and deposit planar cross-beds. Wind constructs dunes and ripples above higher high water, and alluvial fans at the base of beach scarps. Ship wave surge, secondary ship wave swash, and wind generated wave swash deposit bands of pumice grains at the upper limit of water actions on the beach face.

Beach scarps were commonly observed, when present, at the shoreward end of a beach profile. Beach scarps along the lower Columbia are often dramatic features, as seen in Figure 46. Vertical beach scarps are a important response to active wave erosion. Beach scarps are most stable when exposed to wave processes, maintaining a near vertical slope. During periods of little or no wave action the slope of the scarp face tends to decrease, taking on the character of a foredune (Komar, 1976) or becoming

Figure 46. Large beach scarp. Scarp is eroding into 1988 Puget shore nourishment at profile 5. Site is apex of 1988 "shore notch," an active site of erosion.

integrated back into the beach face. Beach scarps were observed to form in previously smooth beach faces, such as that presented in Figure 47.

Sediment grain size distribution across a beach face (Puget Island profile 11) is presented in Figure 48. The histogram illustrates weight percents of four samples down the shore slope and shows that the mean grain sizes increase toward the waterline. This is consistent with most of the established relationships in the literature (Muir Wood and Fleming, 1981; Komar, 1976; USACE, SPM, 1984) which have shown that beaches exhibit long-term sorting of grains normal to slope. Sediment grain size coarsens toward the mean water level from both the landward and riverward directions.

The Shore Notch

One geomorphic feature that was not found in any of the published literature reviewed is the "shore notch." The shore notch is a distinct asymmetric incision into the shore slope with an accretionary lobe in the direction of the incision (Figures 49 to 53). The shore notch appears to be the result of ship wave actions and is the locus of much shore erosion.

Water motions in a shore notch appear analogous to, beach cusps. Beach cusps have been observed on a variety of shorelines (Komar, 1976; Dyer, 1986). Cusps and shore

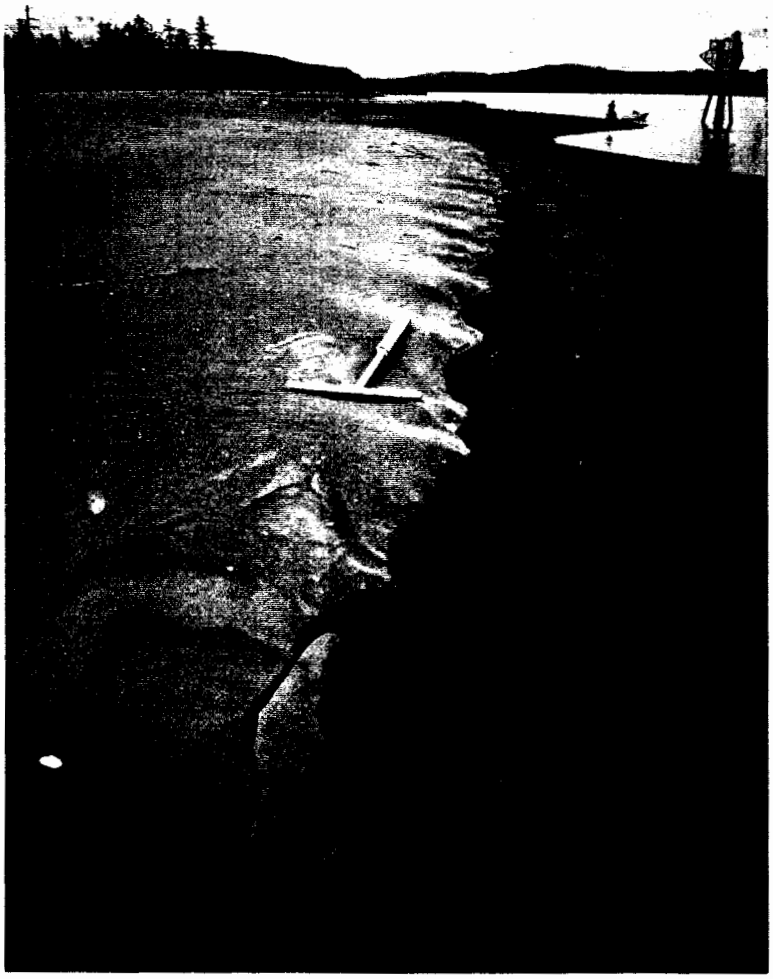
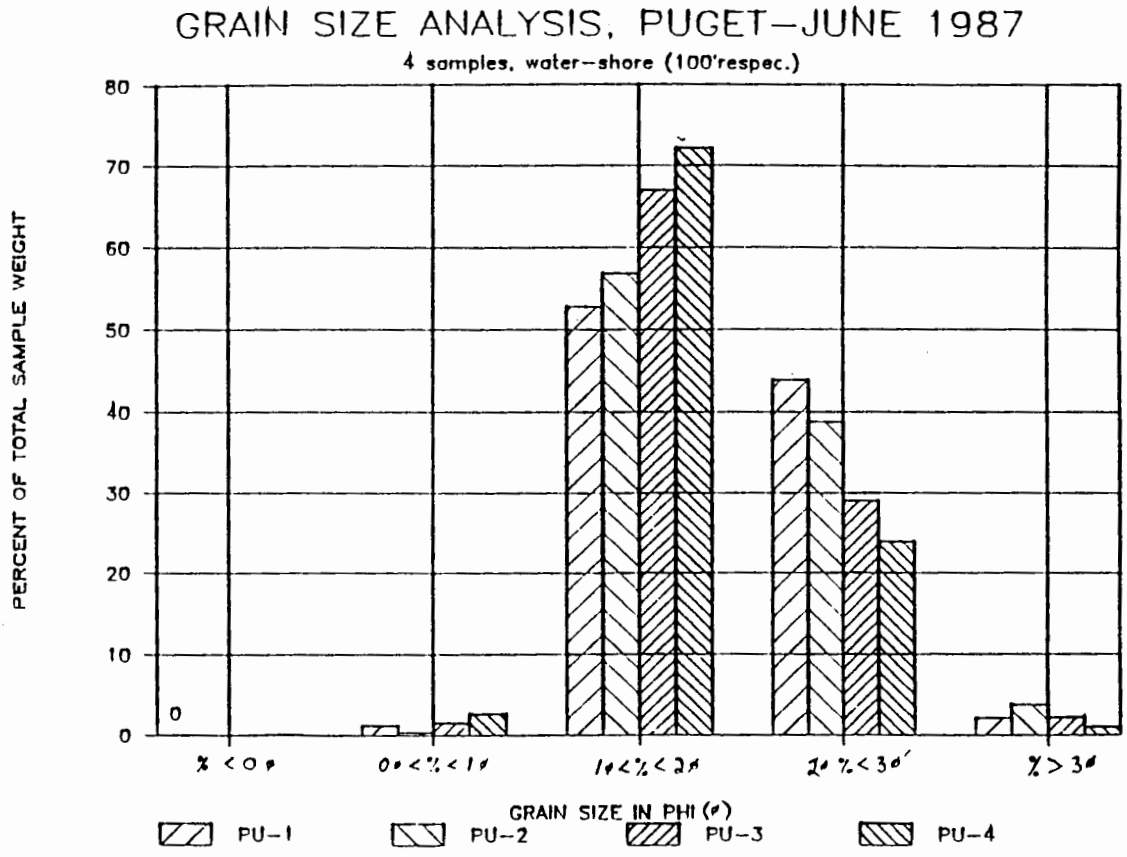


Figure 47. Excellent example of an active beach scarp that has been cut into a previously smooth beach face. Note surface expression of sand above scarp is aeolian, while below is wave swash. Ship wave surge acts similar to wave run-up, attacking the scarp and leading to rapid erosion, as seen in the slump structure near failure in the left foreground. Price Island, 27JUN87.



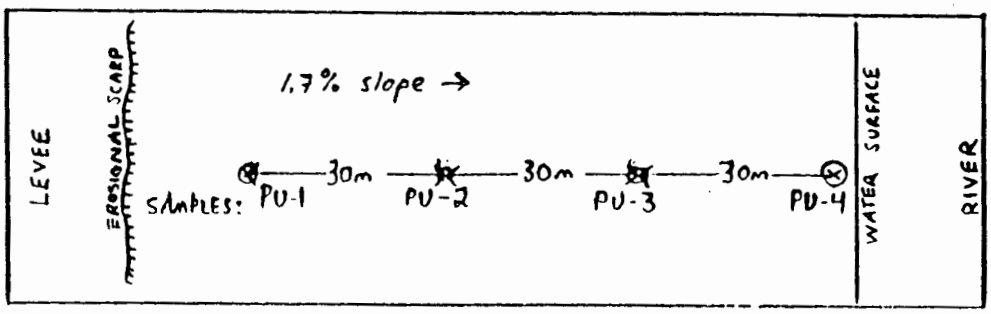


Figure 48. Grain size on a beach face. Grain size variation down a beach face toward the water's edge. Samples are surface grabs on a well developed beach face at the Puget Island site prior to the 1987 nourishment. Note coarser nature and higher kurtosis of sand closest to the water's edge, with fining and lowering of kurtosis of sand population up the beach to samples that have experienced less re-working.

notches are examples of wave refraction over a topographic surface (Komar, 1976; King, 1972; Dyer, 1986). On a low slope beach a spilling wave is refracted so that the wave travels fastest up the cusp valley, or the analogous shore notch, spreads out at the head of the valley, and then travels riverward along the flank of the cusp before dying away. The sediment-laden swash flows along the horns or accretionary lobes, causing them to lengthen. This is apparently the case on the accretionary beach lobes adjacent to the shore notch.

All of the sites profiled, as well as Vista Park, RK WA-54.7 exhibited development of these shore notches. Surge and wave impacts are concentrated at the shore notch.

Figures 49, 50, 51, 52, and 53 all illustrate some of the shore notches observed in this study. Samples were taken at intervals across the 1988 Puget Island shore notch to examine grain size variations (Figure 54). A distinct grain coarsening occurs approaching the apex of the shore notch, as presented in the variation of mean grain size parallel to the shoreline across the shore notch (Figure 55). This grain size distribution corresponds to the distribution of the wave energy across the shore notch. Figure 56 presents a schematic drawing of the relative magnitude of water motions during wave assault at a shore notch. A profile was run parallel to the shoreline at the 1987 Puget Island shore notch to evaluate erosion and

Figure 49. 1987 Puget Island shore notch. Viewed from profile 14, looking north.

Figure 50. Vista Park (RK WA-54.7) shore notch. Note coarser grains accumulating in the notch where the magnitude of incident energy is greatest, and dissipates downstream, resulting in deposition. Thus large grains settle first, closest to the notch, August 26, 1987.

Figure 51. 1988 Puget Island shore notch.

Figure 52. 1988 Puget Island shore notch. Notch developing at profiles PU-4 to PU-8. Looking north-northwest at accreting lobe of beach downstream of notch, June, 1988.

Figure 53. Puget Island shore notch. Looking north, up apex of 1988 notch. Note runnels at base of steep upper beach face below the active beach scarp at the upper right, June 9, 1988.

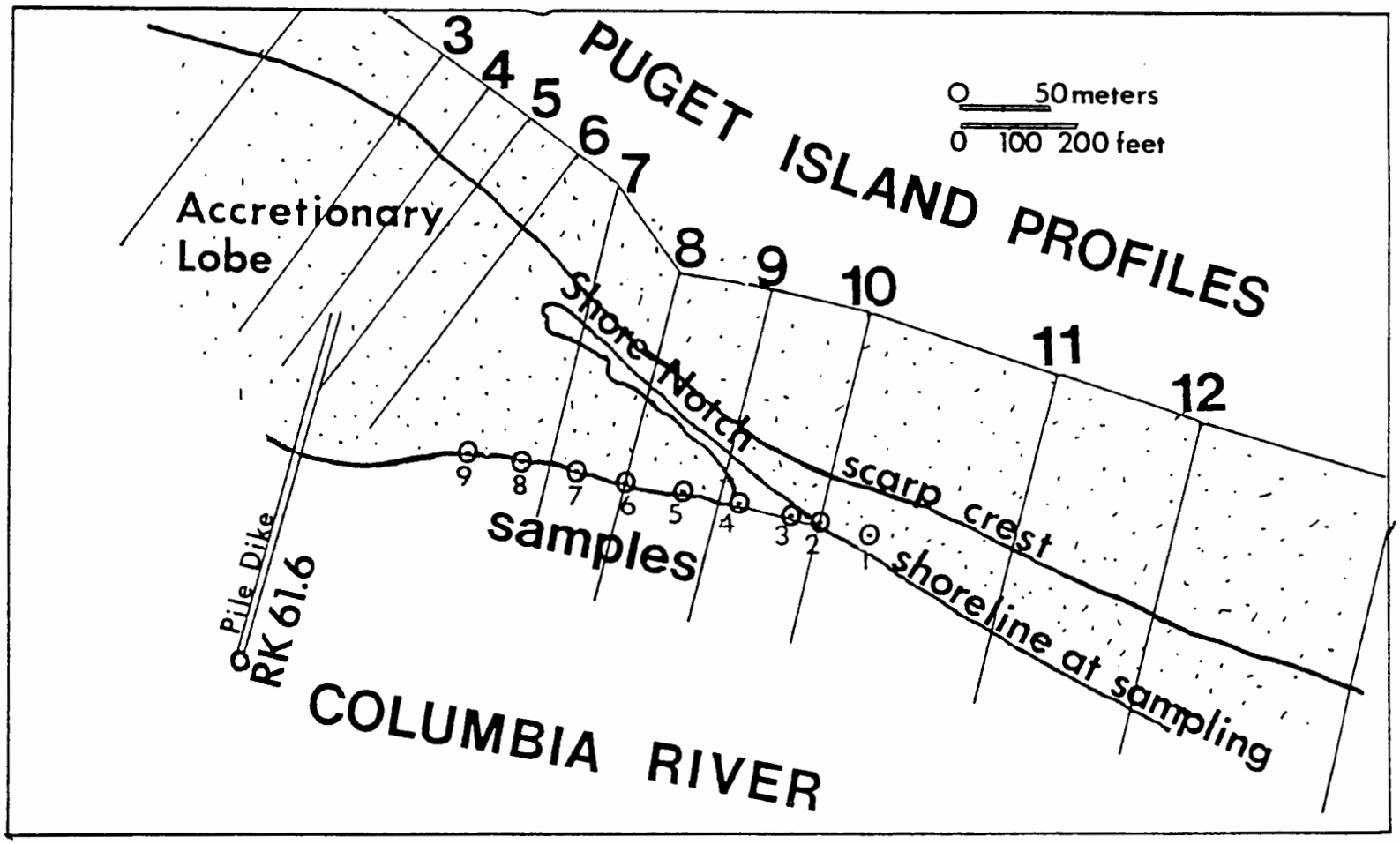


Figure 54. Sample locations. Grain size variation across shore notch (Figure 55).

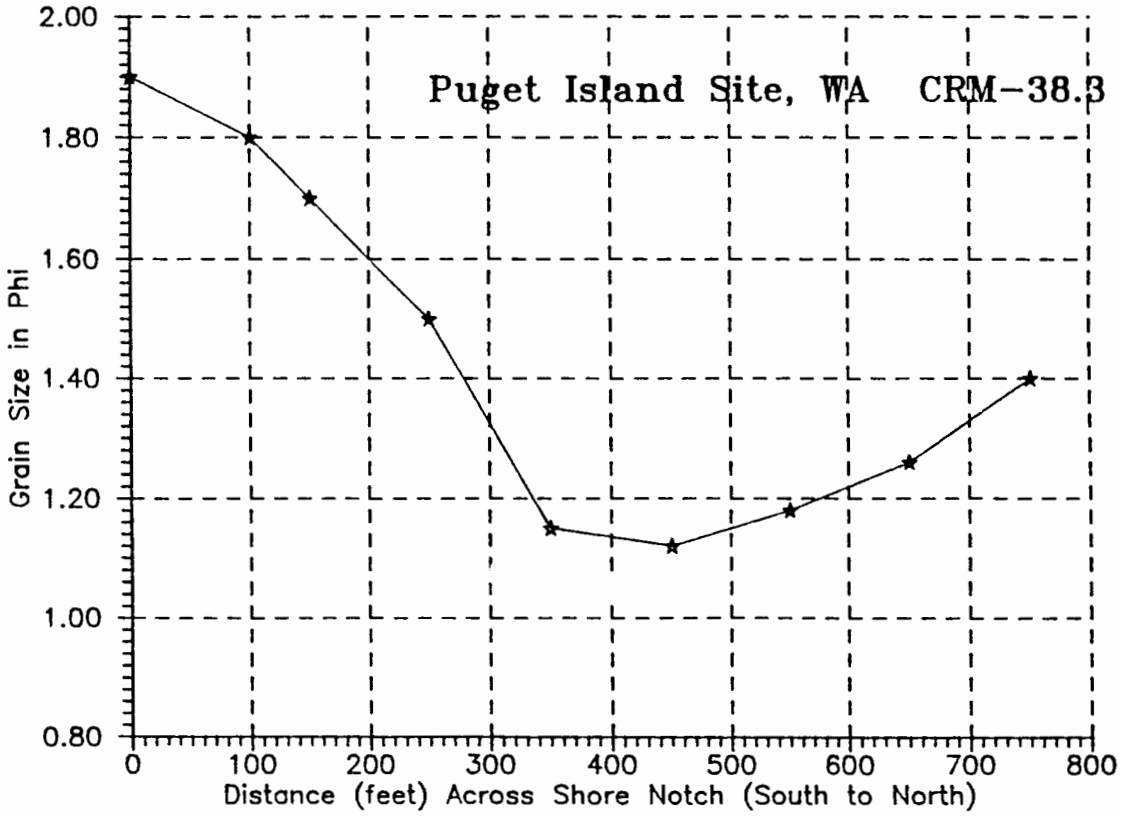


Figure 55. Mean grain size across shore notch. Surface samples taken across an active shore notch (1988 Puget Island site). Graph shows distinct coarsening trend moving across the shore notch. Sample locations are presented in Figure 54.

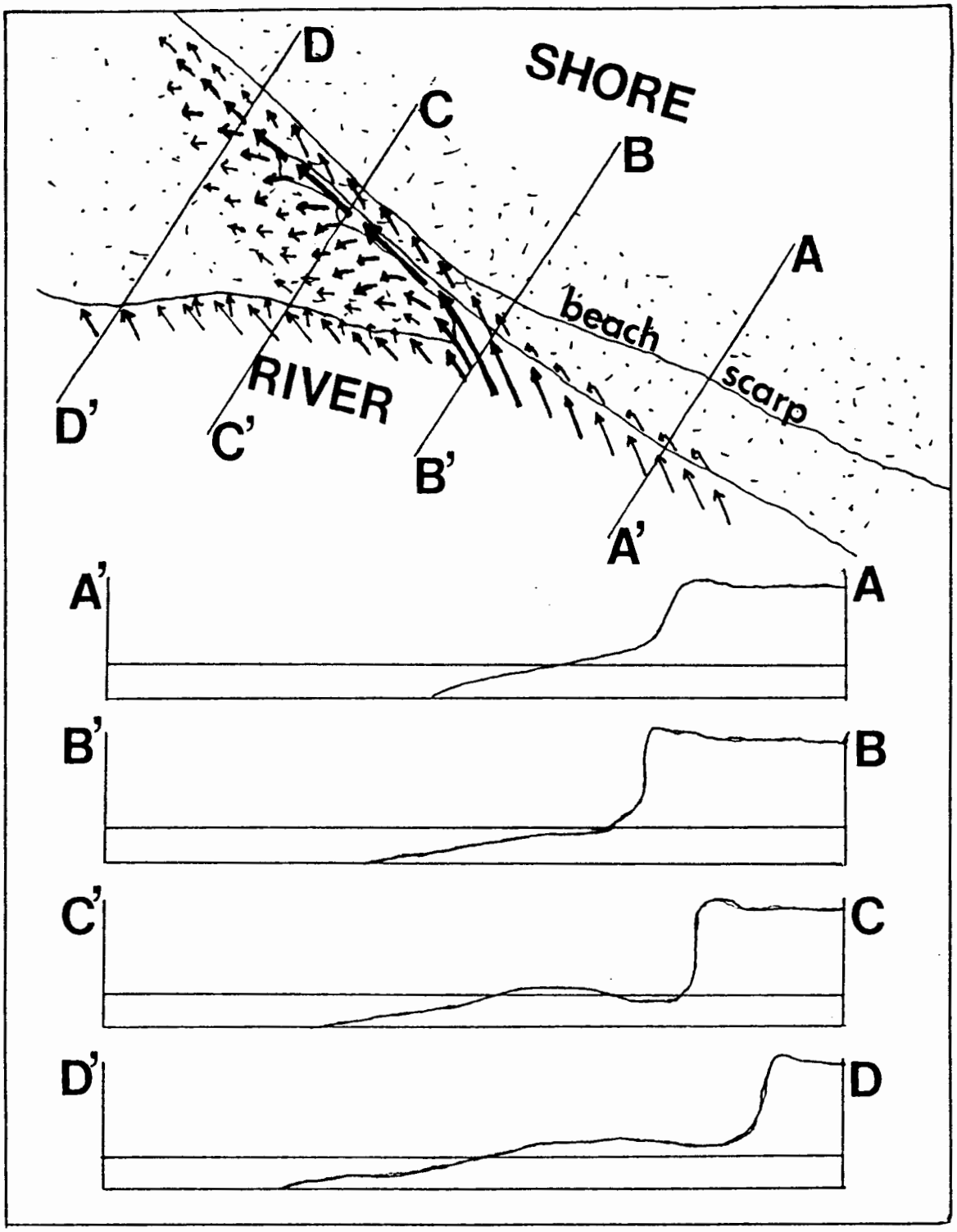


Figure 56. Water motions at a shore notch. Relative magnitude of water motions during wave assault a shore notch and schematic profiles across the shore notch.

accretion. The results of changes seen in one week are presented in Figure 57. Figure 58 shows the accretionary lobe of the 1987 Puget Island site shore notch in the foreground and the zone of accelerated erosion to the upper left.

The headward erosion of a shore notch and deposition of adjacent accretionary lobe was seen in profiling at the 1987 Puget Island shore notch (Figure 57). A breakwall structure at the Puget site made of 5cm * 25cm * 3m wood planks was installed by the landowner with a residence next to the active shore notch. The structure was partially effective in retarding erosion by allowing sediment to accrete on its shoreward side, also providing evidence of a northward longshore drift of sand (in the direction of the notch). The 1987 Puget Island shore notch was buried by a shore sand disposal operation the last week in June, 1987. A new notch developed approximately 300 meters north of this location.

A simple derivation of the volume loss in a unit cell section of the 1987 shore notch produces the following estimations.

8.5 (m^2*m width)/7 days = 1.2 m^2*m/day

1.2 m^2*m/day * 365 days = 443 m^2*m/yr

443 m^2*m/yr * 10 m width of shore notch

= 4,430 m^3 of sand eroded by shore notch and moved onto accretionary lobe.

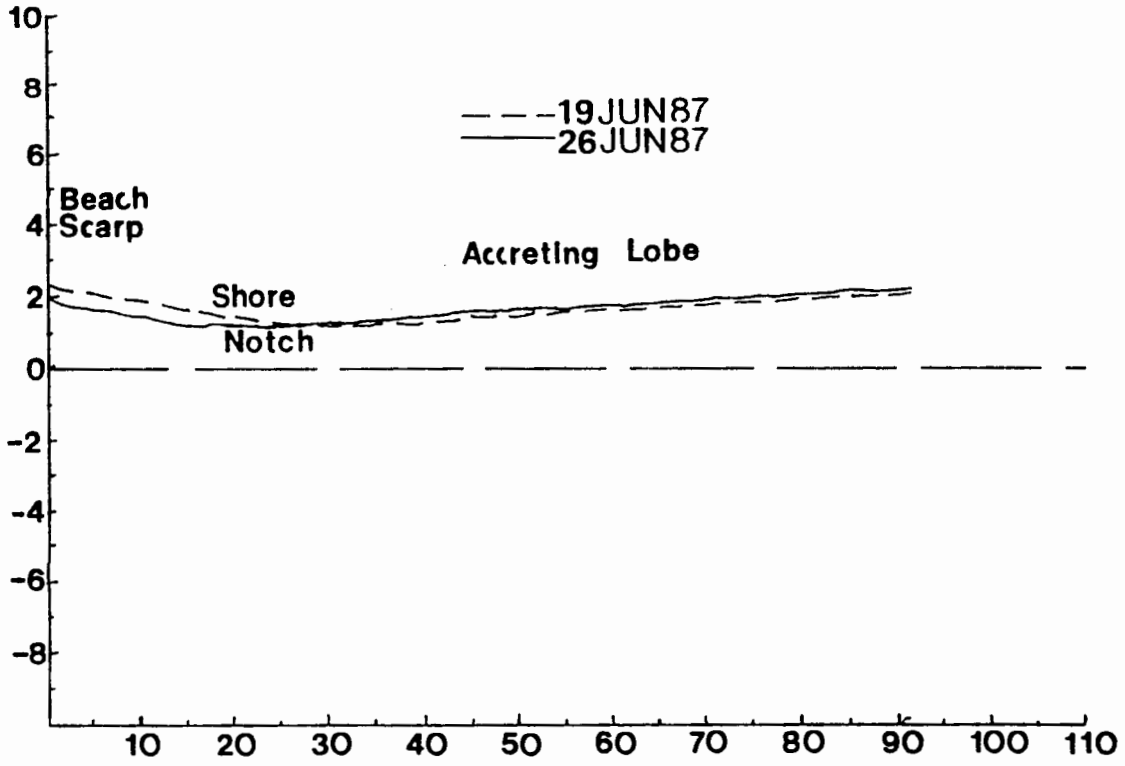


Figure 57. Profiling 1987 Puget Island shore notch. Profiles parallel to shoreline, across the shore notch. Headward erosion is moving upstream.

This estimate of sand transferred from the nourishment to the beach face at the shore notch over a one year period would be equivalent to 17 percent of the sand loss recorded at the Puget site in 1987-1988 (26,197 m^3).

Sedimentary Structures

Observation of sedimentary structures can aid in describing a depositional environment and in determining sediment response to the primary physical processes. The sedimentary character of deposits at shore notches can be

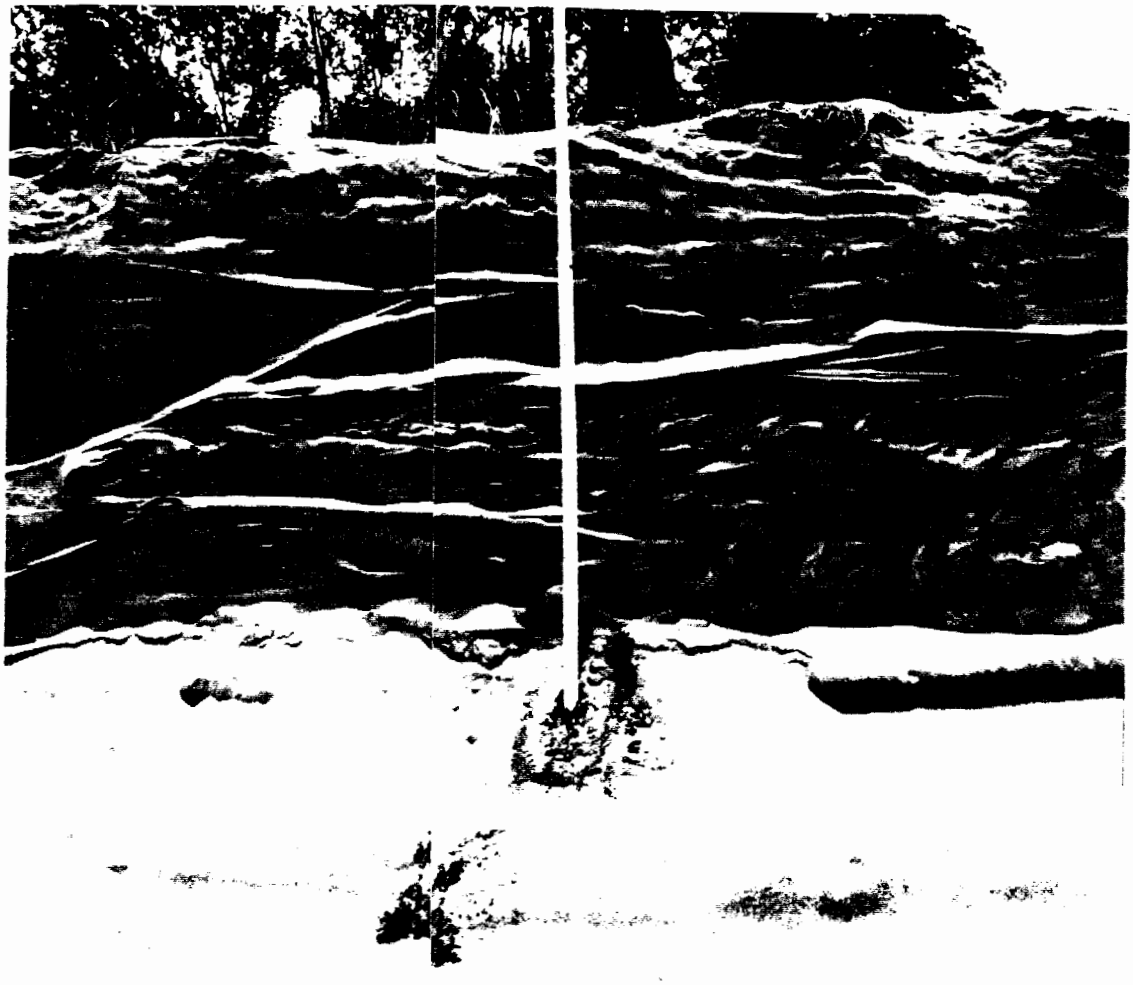


Figure 58. Trough cross-bedding. Trough cross-bedding revealed in beach scarp is characteristic of pipeline sand disposal. Same pattern is exhibited normal to this cut. Puget site profile 10, 17JUN88.63

ascertained by observing exposed sections or by trenching the beach.

The original shore nourishment deposit has a characteristic trough cross-bedding as displayed in the beach scarp of Figure 58. These bedding structures

distinguish the original nourishment from deposits of subsequent reworking. Figure 59 presents a three facies assemblage in the scarp toe cross-section of Puget profile PU-10. Swash lamination can be seen in the top eight cm of the upper beach face trench displayed in Figure 60. Swash laminae are underlain by cross bedding of the original nourishment. The recent nourishment deposition is underlain by low angle planar bedding of the previous beach face. This buried beach shows distinct mineral separation, rippled units, and reactivation surfaces.

Beach features observed at the lower Columbia study sites are presented in Appendix B and are similar to sedimentary structures found in wave and tidal deposits (Reading, 1978; Scholle and Spearing, 1982; Blatt and others, 1980; Araya-Vergara, 1986).

Distinct beheaded ripples (flattened crests) are found in the intertidal zone of the beach face. The ripples are created on the shore slope during high water periods by wind generated waves. As the water level proceeds to lower, wave actions (swash) at the shore-water interface obliterates the ripple crests. The faster the drop in the water level, the better preservation of the ripple forms and as the rate of water elevation change slows (low tide) all ripples are destroyed. Thus ripple preservation is a function time (relative to the tidal curve), wind waves, and ship waves. If a ship passes

Figure 59. Three shore sedimentary facies.

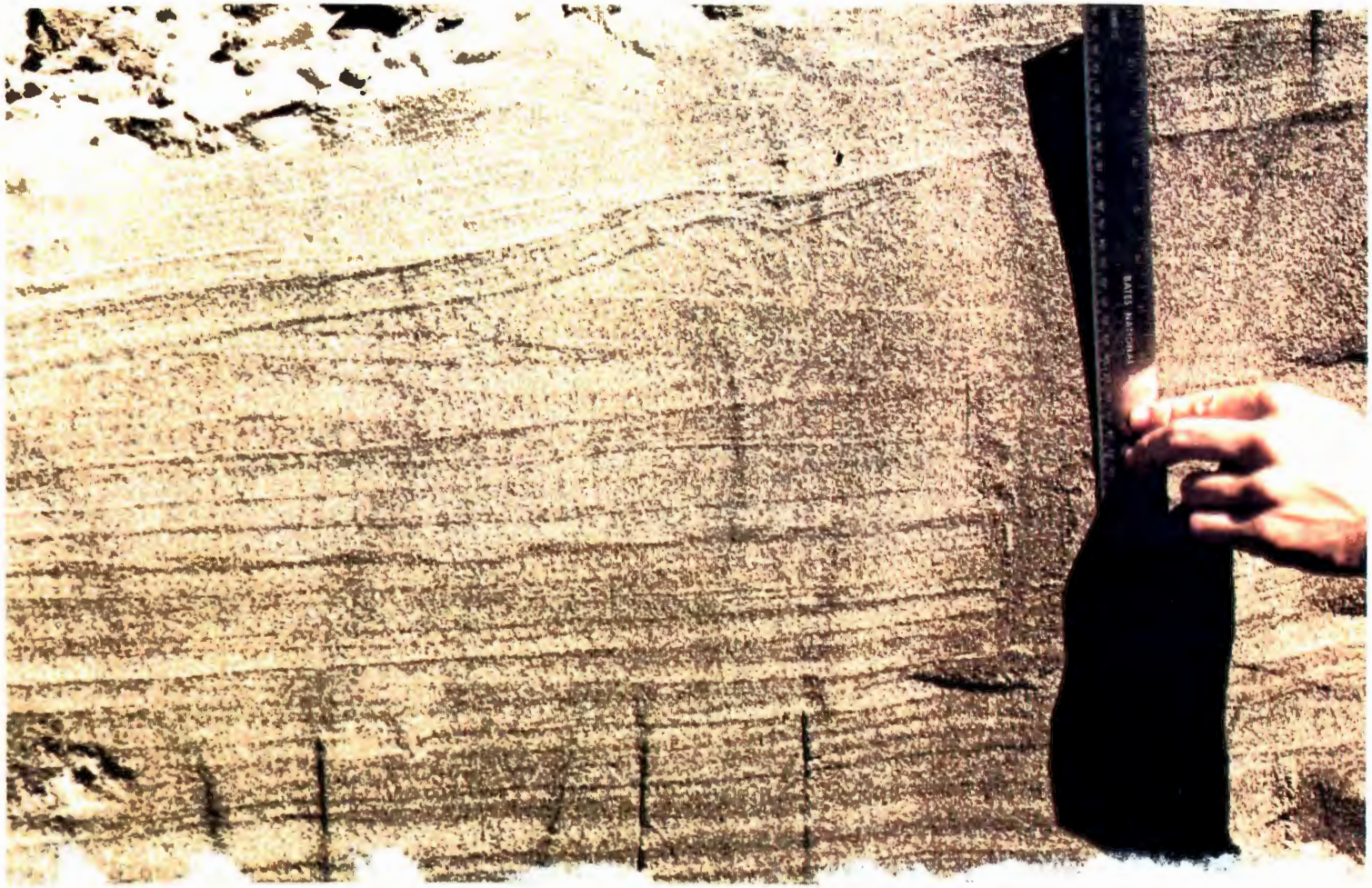


Figure 60. Shore stratigraphy. Riverward of beach scarp. Note reactivation surfaces on oscillatory wave ripples (middle of section) in stratigraphy (characteristic of tidal environment) and heavy mineral laminae (characteristic of tidal peaks).

during the period between a high tide and low tide, the ship waves destroy all of the ripples, precluding preservation. Figure 61 shows a rippled beach at the Puget site and Figure 62 shows the same spot less than one minute later, after one set of ship waves assaulted the beach. Thus considering ships pass a rate of about ten per day (USACE, 1979-1985), it is the norm that the beheaded ripple facies will be destroyed and not be preserved. This is supported by sedimentary sequences observed in shore trenches. The fact that ripples commonly form on shore slopes, but are rarely preserved provides geomorphic evidence of the significant role of ship waves on the shore slopes. Only one rippled bedding surface is preserved in stratigraphic sequence of the trench presented in Figure 59. Measurements of laminae thickness in the upper beach face trench are presented in Appendix B.

Trenches also reveal the stratigraphic character of other distinct environments, such as a tidal flat at the north end the Puget Island site, shown in Figures 63 and 64. Tidal flats characteristically exhibit features such as hummocky bedding; laminae of mud/clay settling out in within troughs; and very low angle shore slopes (Reading, 1978: Scholle and Spearing, 1982). Trenches in the tidal flat reveal settling structures (convolute bedding resulting from differential pore pressures instigated by tidal changes in water level) and pumice swash deposits

Figure 61. Rippled lower beach face. Puget Island, 1988.

Figure 62. Beach face after ship waves. Same exact site as 61, less than 2 minutes later after ship wave assault on the beach face. Ripples are rarely preserved on beach face and in the stratigraphy probably because of the frequency in which ships pass.

Figure 63. Tidal terrace at low tide. Accretionary beach lobe at northern end of Puget Island site. 02AUG88, looking south.

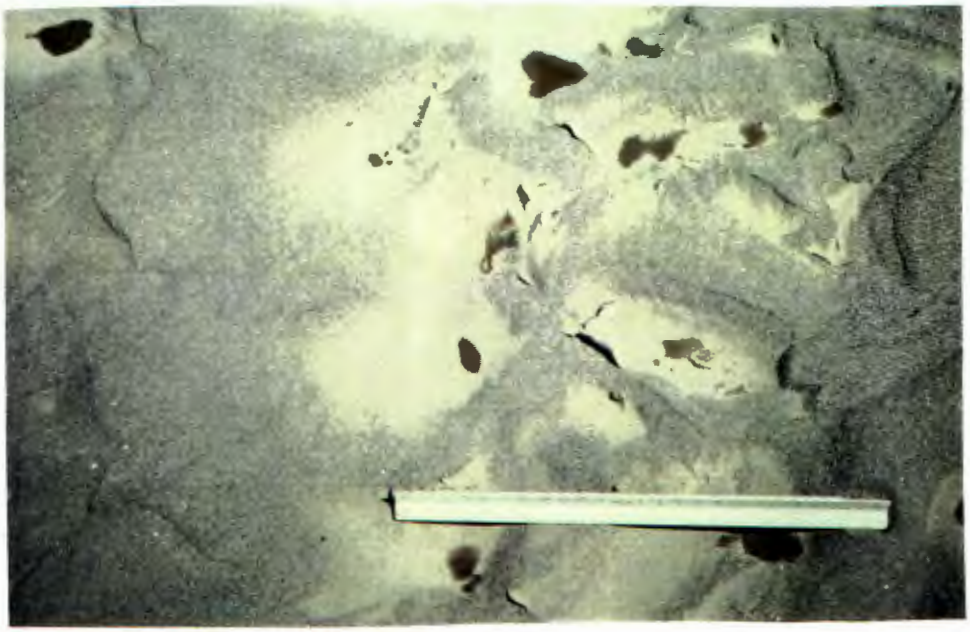


Figure 64. Tidal terrace bedding surface. Same location as 63, this irregular, cuspate trough bedding surface with clay laminae is suggestive of the fluctuating water elevations associated with a tidal environment.

(resulting from wave surge) in the stratigraphy, as seen in Figures 65 and 66.

PHYSICAL FACTORS/PROCESSES

Water Level Fluctuations

Water level changes were derived by linearly interpolating data received from the NOAA tide gauges at Skamokawa, Washington (RK 55) and Wauna, Oregon (RK 72). Water elevations recorded during days on which ship waves were monitored are presented in Table XIV. Flood elevations have been extrapolated by the U.S. Army Corps of Engineers (1988d). Flood events have been well established in coastal science and engineering as a mechanism which enables wave energy to be delivered to the shoreline on an elevated water surface platform (Komar, 1976; MuirWood and Fleming, 1981; USACE, 1984). This action increases the volume of sediment reservoir potentially available to erosion. Floods also bring higher current velocities that can potentially create boundary shear sufficient to cause bank erosion (Dunne and Leopold, 1978). Flood events vary from 3.3 to 4.0 meters above the Columbia River Datum (CRD), as displayed in Figure 67. Geomorphic forms such as beach scarps are indicative of the highest high water elevation on an eroding shore.

Figure 65. Tidal terrace trench. Puget Island, 02AUG88.

Figure 66. Tidal terrace stratigraphy. Convolute bedding, overlying planar bedding more characteristic of a wave dominated beach face.

TABLE XIV

WATER LEVELS AT PUGET ISLAND SITE

Measured on days of ship wave monitoring.
Elevations above National Geodetic Vertical Datum (NGVD)

Date	High High Water (m)	Low Low Water (m)	Tidal Range dZ(m)
09-15-87	1.13	-0.53	1.66
09-16-87	1.30	-0.40	1.70
09-17-87	1.12	-0.60	1.72
09-18-87	1.30	-0.53	1.83
10-29-87	1.67	-0.57	2.24
10-30-87	1.67	-0.57	2.24
06-08-88	1.70	-0.27	1.97
06-09-88	1.93	-0.20	2.13
06-13-88	1.80	-0.63	2.43
06-14-88	1.83	-0.60	2.43

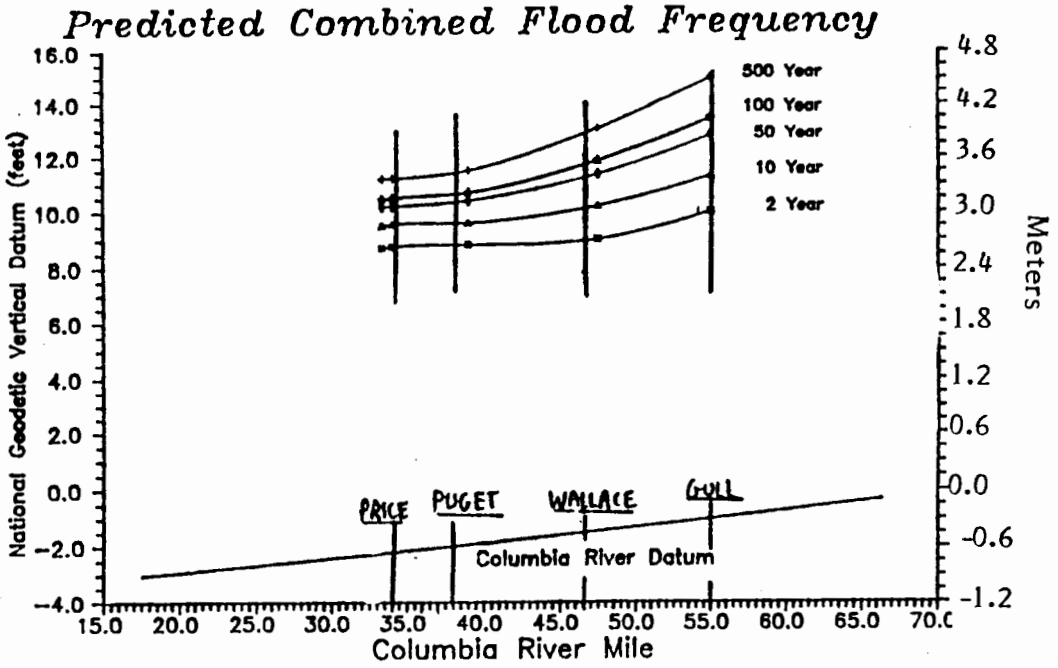


Figure 67. Combined flood frequency. Lower Columbia River. NGVD (1 ft = .3048 m) versus Columbia River Mile (CRM, 1 mi = 1.61 km). Columbia River Datum (CRD) is given for reference (Navigation channel depth is maintained in reference to the CRD).

Channel Geometry

The geometry of a river channel will directly control velocity regimes, ship waves, and wave decay, reflection, and refraction along the shore. Figure 68 presents the channel cross-section of the Columbia River adjacent to the Puget Island site. Table XV presents the variation in lower Columbia river channel size based on thirty-one cross-sections from River Kilometer 59.9 to 102.3.

Describing flow in a channel must account for the channel boundaries. A small fraction of river's boundary is the region was examined. The channel morphology

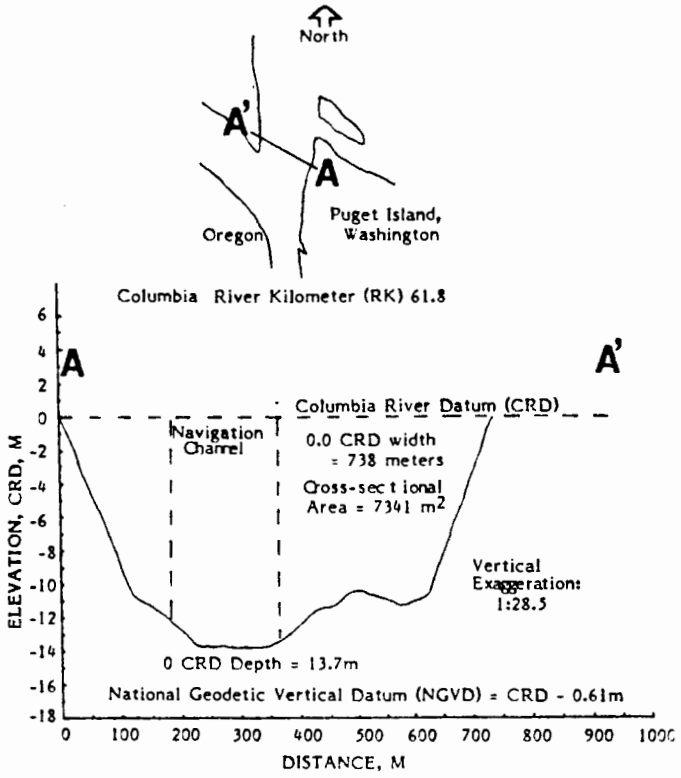


Figure 68. Columbia River cross section at Puget Island site. Data for cross section is from January 13, 1988 bathymetry by the U.S. Army Corps of Engineers, Portland District.

directly affects the hydraulics of both flow velocities and ship waves. When channel cross-sectional area increases, flows tend to decrease (illustrated in historical bathymetric maps of the river), a relationship presented quantitatively in Mannings Equation (2):

$$V = C_m/n * A * R^{0.75} * S^{0.50} \quad (2)$$

where: C_m = 1.0 (SI units)

R = A/P (hydraulic radius)

P = wetted perimeter of channel

A = cross sectional area of channel

TABLE XV

COLUMBIA RIVER CROSS-SECTIONS

River Kilometers 59.9 to 102.3

Surface width of channel at 0 CRD

n	=	31
n_{max}	=	564 m
n_{min}	=	206 m
μ	=	377 m
m	=	381 m
σ	=	92 m
R	=	358 m

Cross-sectional area at 0 CRD

n	=	31
n_{max}	=	11,260 m^2
n_{min}	=	6,612 m^2
μ	=	8,889 m^2
m	=	8,927 m^2
σ	=	1,171 m^2
R	=	4,648 m^2

where n = number of sections

μ = mean of sections

m = median of sections

σ = standard deviation

R = range of values

w = surface width of river

V = average velocity

n = absolute roughness coefficient

S = slope of channel bottom

Ship wave magnitude will be dampened with channel cross-sectional area (Sorensen and Weggell, 1984; Brebner and others, 1966; Johnson, 1968). The confluence of the main river channel with the Clifton Channel west of the northwest end of Puget Island increases the cross sectional area of the river, decreasing water velocities and resulting in a region of historical shoaling.

The threshold of sediment motion is partially a function of water velocity, as presented in the Hjulstrom curve (Hjulstrom, 1939) shown in Figure 69. Flow velocities are a function of channel geometry, discharge, water surface slope, and tide.

WIND

Winds in the study region builds dunes up to several decimeters in height and sort sand grains. Examination of dunes suggest that winds predominantly blow from the west, northwest. Average monthly wind velocities gaged at Astoria, Oregon between 1941 and 1976 show a two dominant wind directions; from the west, northwest in the spring and early summer; from the east, southeast in the fall and winter (Table XVI). The annual mean wind velocity at Astoria, Oregon is 3.75 m/s. Using this mean velocity

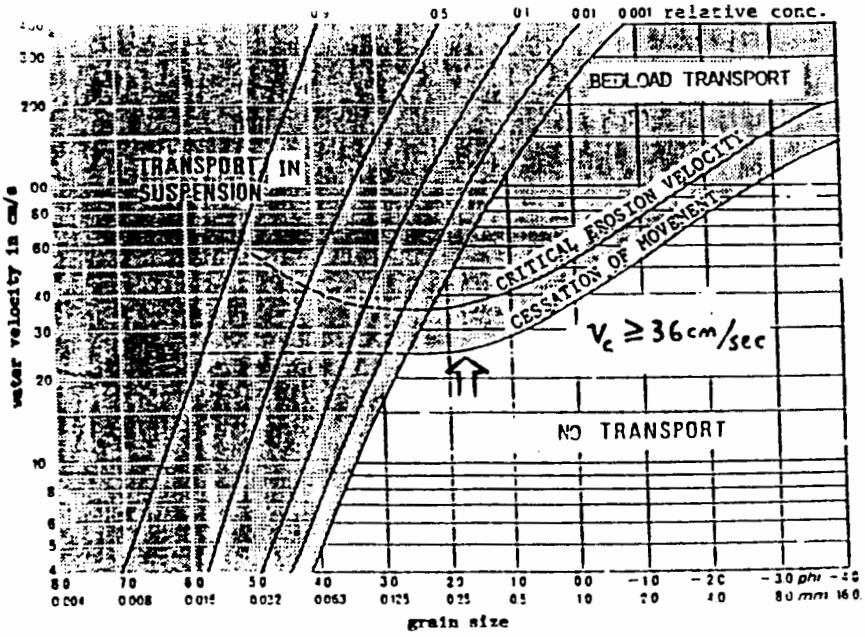


Figure 69. Hjulstrom (1939) Curve for estimating critical threshold velocity of quartz grain (sp. gr. 2.65) for range of grain sizes (Sundborg and Norrman, 1963).

estimated mean annual surface current generated by wind shear at the surface of the water is 0.11 m/sec, producing near bed velocities well below the threshold of sand.

Table XVII presents orientations of dunes recorded the summer of 1988 at the Puget Island site, which consistently presented evidence of a dominant westerly or northwesterly wind direction (blowing from the west/northwest).

Dune crests are composed of distinctly coarser grains than dune troughs. The coarser grains generally are too large for existing wind shear whereas the small grains can be more easily moved. The small grains migrate to areas of decreased wind shear (conditions below threshold).

TABLE XVI

AVERAGE WINDS AT ASTORIA, OREGON

Month	Prevailing Direction	Velocity (m/sec)
January	E	4.20
February	ESE	3.93
March	SE	3.98
April	WNW	3.84
May	NW	3.75
June	NW	3.66
July	NW	3.75
August	SE	3.49
September	SE	3.26
October	SE	3.35
November	SE	3.75
December	ESE	4.07

(Beeman, 1985)

TABLE XVII

SYMMETRICAL EOLIAN DUNE ORIENTATIONS

Puget Island Site, July 31, 1988

Crest Azimuth (deg)	Transport Azimuth (deg)
1	91 (east)
3	90 (east)
350	80 (east)
0	90 (east)
356	86 (east)
4	91 (east)
14	104 (east)
359	89 (east)
355	85 (east)

Selective transport of the fines leaves concentrations of coarse grains (dune crests). Dune troughs are sheltered from the wind and thus host the finer grain sizes.

Wind Generated Water Waves

Wind generated water waves can be predicted using established theory and empirical relationships (USACE, 1984). The dominant easterly winds (tables XVII and XVIII) that occur from the early Fall (August) to early Spring (March), have a mean velocity of 3.7 m/s. The effective wind stress is derived using the empirical expression presented in Equation (3) (USACE, 1984):

$$U_A = 0.71\ U^{1.23} \qquad (3)$$

where: U_A = wind shear stress velocity

U = wind velocity (m/s)

The above expression can used in Equations (4) and (5) with a known shallow water depth (constant in theory) and a fetch distance to estimate significant wave height and period.

$$[gH/U^2]=0.283\tanh[0.530(gd/U^2)^{3/4}]* \tanh\{[.00565(gF/U^2)^{1/2}]/\tanh[.530(gd/U^2)^{3/4}\} \quad (4)$$

$$[gT/U]=7.54\tanh[.833(gd/U^2)^{3/8}]\tanh\{[.0379(gF/U^2)^{1/3}/\tanh[.833(gd/U^2)^{3/8}]\} \quad (5)$$

Southeasterly winds at the Puget Island site blow right off the island and thus are assumed to have negligible effect on the generation of water waves at the site. The fetch from the Northwest at the Puget Island site is approximately 1.6 kilometers and an average depth of 25 to 30 feet. The predicted significant wave height (wave height that is greater than 2/3 all waves) is 7 cm and has a period of 1.04 seconds. Ofuya(1970) used wind wave data to estimate the annual energy delivered to a shoreline in ft.lbs/ft of shoreline with Equation (6):

$$W_w = (10* [(H_s^2 T_s)_n (T_d)_n]_q)/(DY*24) \quad (6)$$

where: q = 1,2,...q represents the wind directions N, NNE, NE, etc.

n = 1,2,...n represents the wind speed class, i.e. 1 mph (mile per hour), 2 mph, etc. at the given site.

H_s = significant wave height

T_x = significant wave period

DY = number of days this wind occurs

W_w = energy prorated (work done) to the shore per hour.

For the Puget site, the above equation is used with the following variables:

q = 1

n = 1

H_s = 0.23 ft (.07m)

T_s = 1.04 sec

T_d = 86,400sec (24 hrs)

DY = 155 days

Thus W_w = 47,534/(155*24) = 12.8 ft.lbs/ft of shoreline or 56.9 Newton-meters/meter. This derivation used a DY value of five months, a conservative value based on the wind data presented in Table XVII.

Assuming the following criterion:

U (wind velocity)	=	3.7 m/s
d (depth)	=	9.1 m
F (fetch)	=	1.6 km
H_s (sig. wave height)	=	.07 m
T_s (sig. wave period)	=	1.04 sec

and using Equation (7) for energy flux, P_{lb} (USACE, 1984):

$$P_{ls} = ((pg)/16)H_{sb}^2 C_{gb} \sin(2\alpha_b) \quad (7)$$

where: C_{gb} = wave speed = 0.62 m/s

H_{sb} = sig. breaking wave height = 0.07 m

α_b = wave incidence = 10^o

P_{ls} = 6.34×10^{-4}

Using the empirical expression (8), derived from the data of Bruno and others (1981, IN: USACE, 1984):

$$Q\ (m^3/yr) = 1290\ (m^3\text{-}s/N\text{-}yr)\ P_{ls}\ (J/m\text{-}s) \qquad (8)$$

$Q = 0.82\ m^3/yr$ = annual longshore transport flux

This derivation suggests that longshore transport due to wind waves at the Puget Island site is negligible.

Effect of Wind on Beach Morphology

Wind is the secondary eroding agent (next to water actions) of beach scarps. The rate of work done by the wind directly control the scarp's slope when it is not exposed to water. Water actions cut into the upper beach creating a beach scarp and moving sediment out onto the beach face, leaving a near vertical incision on the beach. Wind actions will rapidly modify this vertical scarp by blasting the scarp's face and sending grain flows streaming down the scarp to coalesce into "micro-bajadas" or miniature alluvial fan forms on the beach face, illustrated in Figure 70. The rapid work of wind was illustrated by a simple experiment in which a vertical cut was made into a beach well above high high water (thus precluding any water actions from affecting the cut). same site two days later and Note the distinct "micro-hoodoo" type pillars of sand that form and the coalescing fans at the slope's base. The

Figure 70. Eolian slope, beach scarp. Wind build distinctive fan like deposits which coalesce to form "micro-bajadas", such as ones at bottom of the photograph, forming at most recent beach scarp. Wallace Island site, June 24, 1988.

experimental scarp was surveyed immediately after it was cut and again in two days, the result is presented in Figure 71. Fan deposits rapidly developed at the scarp toe. Rapid slope development occurs at a the beach scarp when exposed to wind actions. The distinctive dune above the artificial beach scarp (Figure 71) is a characteristic eolian feature on the shorelines that hosted large beach

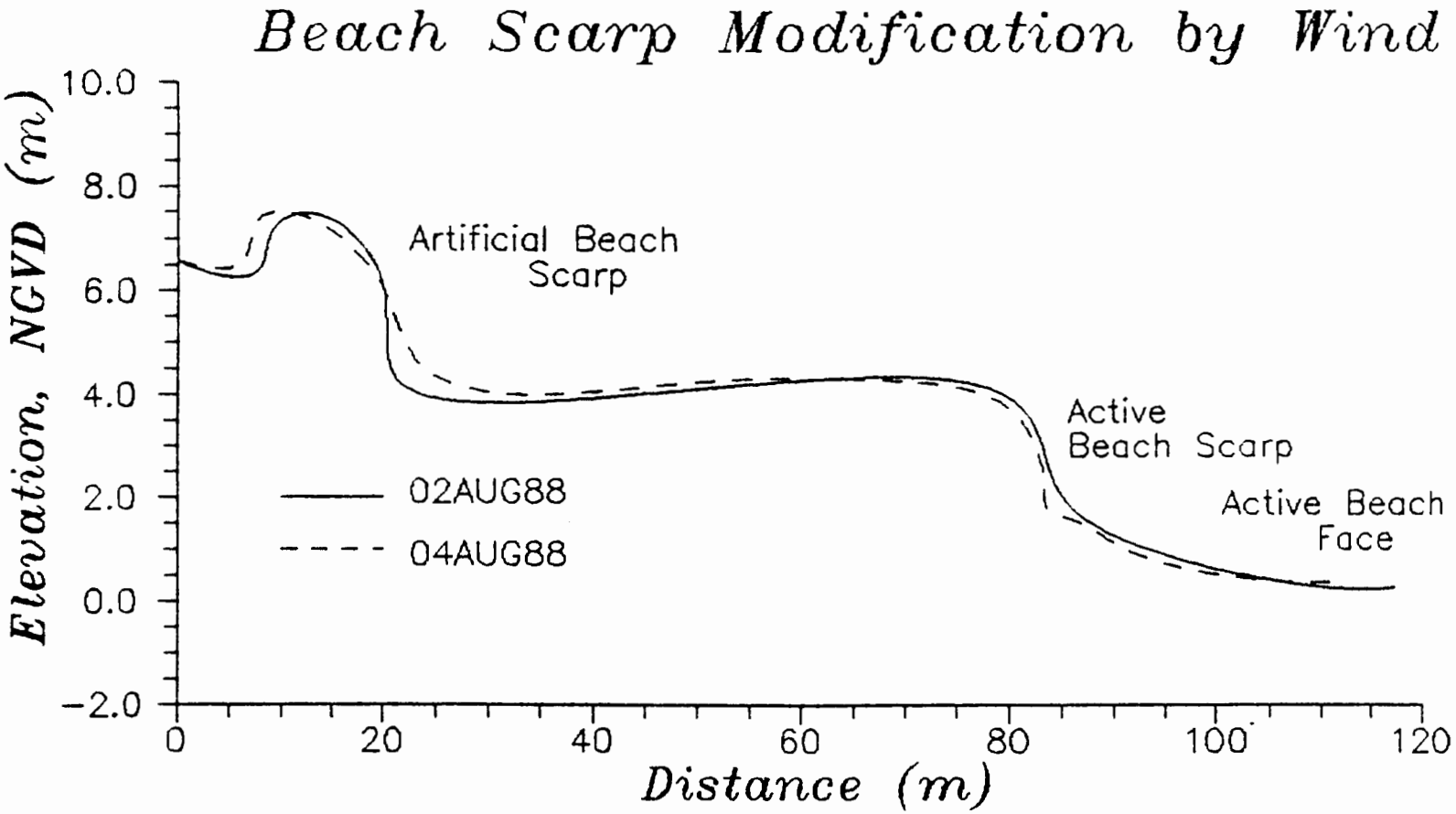


Figure 71. Puget Island profile 4. After 1988 nourishment to examine the changes at a large beach scarp due to wind, between August 2 and August 4.

scarps. This experiment suggests that the vertical slope of west facing beach scarps along the Columbia is a shore lived phenomena without repeated exposure to water actions.

Background River Hydraulics

A current trend in coastal, estuarine, and fluvial studies is mathematical model simulations of the hydraulic system. The present state of mathematical models is such that they must be used with care in evaluating and predicting a system. This is especially true in a tidal environment of flow reversals, as shown by Roovers and others (1981) in an analysis of sedimentation in an estuary/harbor along the coast of Belgium. The region exhibits high current velocities of up to approximately 1.50 m/s during spring tides. The sediment is fine sand and silt. In the Columbia River Estuary the conditions have some similarity. Material transport in these types of systems is considerable and morphological instability appears quickly when changes occur in the hydraulic regime (Roovers and others, 1981). Calculation of sediment transport by currents is prone to considerable variance from the real system, especially when tides come into play, where calculations are very sensitive to minor changes or inaccuracies (Roovers and others, 1981). The five cm/s error in the analysis of Roovers and others (1981) can result in a complete reversal of the erosion and

sedimentation pattern. This can be critical in analysis when the flood (upstream flow) stream is 1.0 m/s and the ebb (downstream flow) stream 0.9 m/s, the difference being only 10 cm/s. Transport in tidal environments is attributed to the "differential" or difference between the two quantities, flood and ebb flows.

Modeling has been done in the Columbia Estuary and the Price Island-Puget Island regions, using a two dimensional vertically integrated numerical model RMA-2 (TABS-2) for open-channel flow and sedimentation (Sedimentation Section, Portland District, USACE, 1986-1988). This model has been used by the Portland District of the Corps of Engineers in evaluating hydraulic patterns with and without structural controls such as pile dikes and submerged groins. The model is used in this study to estimate channel current velocities, for a prototype discharge and tide. Using prototype data from June 1986, the model predicted a maximum flood current of about 0.61 m/s (2 ft/s) and a maximum ebb current of about 1.22 m/s (4 ft/s). Figure 72 plots water elevation and velocities (mid channel and near Puget boundary) predicted by the model in the main channel of the Columbia adjacent to the Puget Island site using prototype data from June 1986 (discharge of about 8,500 m^3). The lag is a function of the river's changing surface profile. When a equilibrium of the currents upstream and downstream of the site is reached

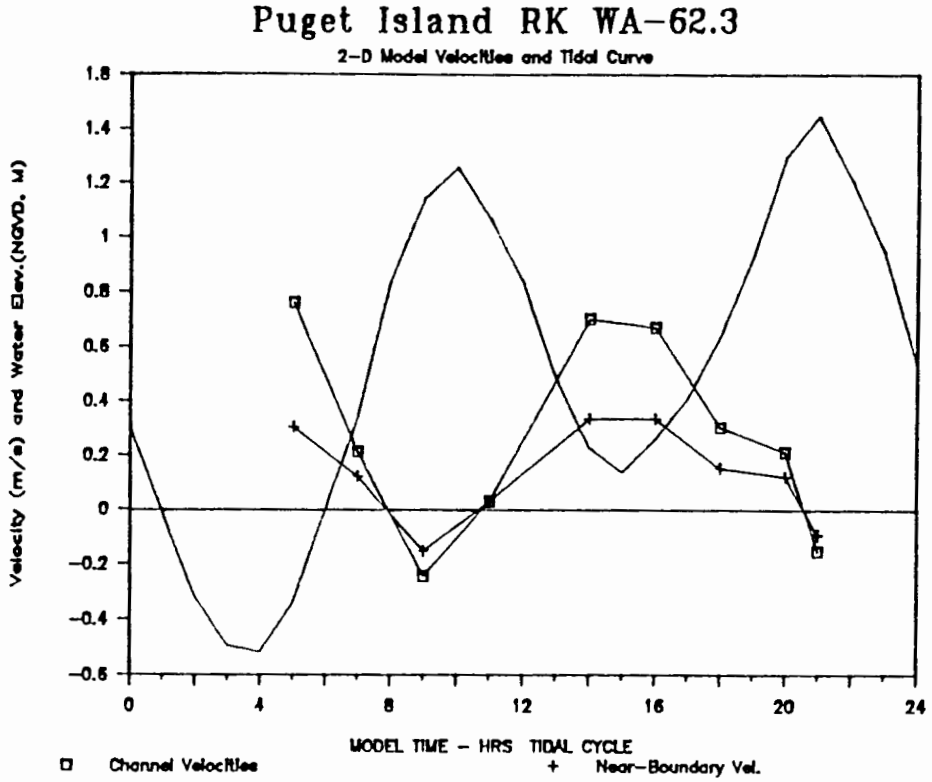


Figure 72. Model results of ebb flows. Plot of tidal curve, mid-channel, and near-boundary vertically integrated velocities at the Puget site, as predicted by the two dimensional model RMA-2.

then slack water will be obtained. Because the model runs were based on one set of daily current data, the true velocities could vary significantly. Nearshore surface velocities done provide estimates of currents in shallow water. The model can supply approximate conditions and responses in the channel, but becomes much less reliable in the shallow near shore area where processes other than tidal and freshwater currents become the controlling

factors. For a more complete discussion of model results, refer to Eriksen (1989).

SHIPS

The ships examined in the study cover a variety of vessel types, presented in Table XVIII.

The total number of ships drafting 6 meters or more moving transiting the lower Columbia is between 3,000 and 3,700.

Predicting Ship Wave Height

Several empirical methods have been published to predict secondary ship wave size (Saunders, 1975; Sorensen and Weggell, 1984). The solutions for ship wave predictions presented by Saunders (1975) and Sorensen and Weggel (1984) and Barrass's (1979) solution for ship squat to compare with measured wave heights and drawdowns, respectively, made in this study (Appendix C). Squat is the lowering of the water surface adjacent to a ship relative to the existing water surface, bringing the ship closer to the channel bed. Drawdown is the lowering of the water surface along the shore as a ship moves by. It is assumed that ship squat is the driving mechanism instigating drawdown along the shoreline, thus it should be of a greater magnitude than drawdown.

Equations (9 - 14) present the set of derivations presented by Sorensen and Weggell (1984) based on field

TABLE XVIII

SHIP PASSAGES

Ship Type	Number of Passages*
o Bulk Carriers	10
o Container Vessels	2
o Tankers	3
o Car Carriers	1
o Naval frigates	5
o Naval destroyers	1
o Naval supply ships	2

*Note: Observed passages only for this study and are not representative of total shipping on the lower Columbia River. Only some of these ship events were also analyzed for sediment transport.

data collected by Sorensen (1973) and further calibrated using laboratory data of Das (1969) by Sorensen and Weggell (1984). Variables were converted into dimensionless units using a denominator of volume (L^3; L=length units); the ship's displacement.

H = ship generated wave height (L)

d = water depth (L)

x = distance to sailing line (L)

V = ship velocity (L/T)

SD = ship displacement (L^3)

SL = ship length (L)

SB = ship beam (L)

SS = ship draft (L)

L = length units

T = time units

Dimensionless Variables as defined by Sorensen and Weggell (1984) are listed below:

$F = V/(gd)^{0.5}$ = Froude number

$H^* = H/SD^{0.33}$ = dimensionless wave height

$x^* = x/SD^{0.33}$ = dimensionless distance from sailing line

$d^* = d/SD^{0.33}$ = dimensionless depth

$SL^* = SL/SD^{0.33}$ = dimensionless ship length

$SB^* = SB/SD^{0.33}$ = dimensionless ship beam

$SS^* = SS/SD^{0.33}$ = dimensionless ship draft

Equation (9) is the general expression to predict ship wave height is (Sorensen and Weggell, 1984):

$$H^* = \alpha x^{*n} \tag{9}$$

where $n = \beta(d^*)^{\delta}$

$\beta = -0.225F^{-0.699}$ 0.20 .LE. (F) .LE. 0.55

$\beta = -0.3420.55$ .LE. (F) .LE. 0.80

$\delta = -0.118F^{-0.356}$ 0.20 .LE. (F) .LE. 0.55

$\delta = -0.1460.55$ .LE. (F) .LE. 0.80

$$\log\alpha = a + b(\log(d^*)) + c(\log^2(d^*)) \tag{10}$$

$a = -0.6F$

$b = 0.75F^{-1.125}$

$c = 2.653F^{-1.95}$

The final calculated value of (H*) was corrected (Sorensen and Weggell, 1984) to measured model values (Das, 1969)

using the following linear equations dependent on the model hull configuration:

Box Hull:

$$H^*_{mea}=2.427H^*_{calc} - 0.0728 \quad (11)$$

Cruiser (Broad beam):

$$H^*_{mea}=3.158H^*_{calc} - 0.1105 \quad (12)$$

Mariner (most streamlined):

$$H^*_{mea}=0.835H^*_{calc} - 0.0225 \quad (13)$$

The derivation for ship wave height presented by Saunders (1975) is presented in Equation (14):

$$H = kw[(B/LE) * (V^2/2g)] \quad (14)$$

where: kw = coefficient (used 1.0)

SB = ship beam

LE = distance from bow to midbody

V = ship velocity

g = acceleration due to gravity

Terms for Table XIX:

H1 = wave height predicted without linear correction (Sorensen & Weggell, 1984)

H2 = wave height predicted (Saunders, 1975)

H3 = measured wave height , m = meters, others defined above

The results of these ship wave prediction calculations are presented in Figure 73. Observed drawdown sometimes (though uncommon) exceeded predicted drawdown

TABLE XIX

CALCULATED VALUES OF SECONDARY SHIP WAVE HEIGHT

Ship	SD	F	n	α	H*	H1	H2	H3	Hull
Ocean Beauty	16636	.46	-.43	.064	.024	.61	.34	.27	C
Chevron Oregon	37602	.27	-.68	.015	.004	.13	.13	.17	C
Magnolia	30127	.37	-.53	.040	.013	.41	.24	.38	C
Kee Lung	22612	.41	-.41	.050	.018	.49	.30	.15	C
Luna II	33381	.37	-.53	.042	.014	.45	.26	.31	C
Lake River	38815	.42	-.49	.064	.024	.81	.30	.16	C
Leandros	34446	.36	-.51	.039	.014	.45	.22	.15	C
European Highway	12437	.35	-.52	.025	.007	.17	.26	.30	C
Coast Range	27685	.38	-.52	.042	.014	.42	.25	.11	C
Ocean Jade	28950	.28	-.65	.015	.004	.12	.14	.28	C
Verrazano Bridge[1]	18176	.38	-.50	.037	.012	.31	.21	.19	C
Verrazano Bridge[2]	31638	.40	-.50	.052	.018	.58	.23	.61	C
Indah Fuji	16714	.40	-.48	.043	.014	.37	.30	.19	C
USN Chandler	6210	.38	-.48	.029	.008	.15	.17	.21	M
USN Ford	2750	.42	-.42	.038	.011	.16	.21	.42	M
USN Thach	2750	.37	-.46	.024	.006	.09	.17	.08	M
USN Gray[1]	3011	.41	-.43	.035	.010	.15	.22	.43	M
USN Gray[2]	3011	.34	-.49	.018	.004	.06	.15	.36	M
USN Ramsey	2640	.38	-.45	.027	.007	.10	.27	.38	M
USCG Boutwell	3050	.42	-.43	.038	.011	.16	.24	.34	M
USCG Iris	935	.31	-.49	.012	.002	.02	.23	.23	C

[1] = inbound [2] = outbound

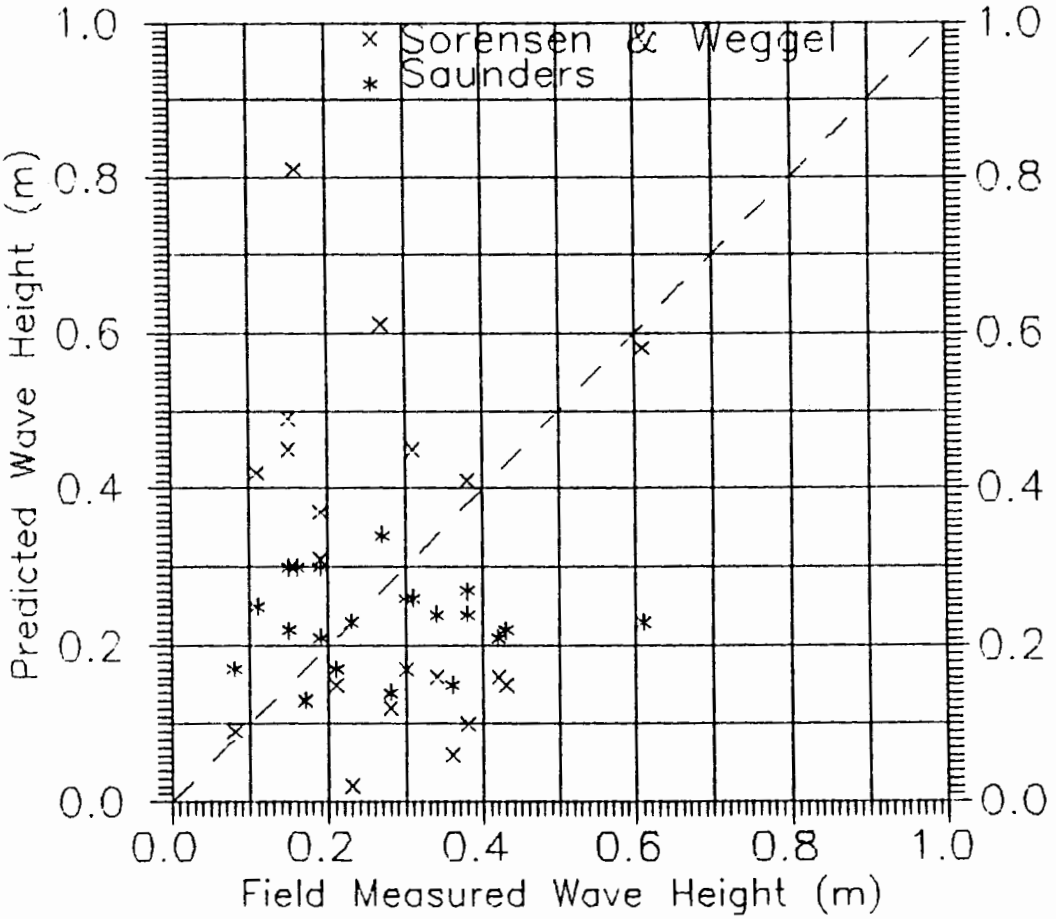


Figure 73. Predicted versus measured ship wave heights.

which should always have been greater then drawdown at the shore.

Ships transiting the lower Columbia River often have draft to depths approaching the maintained channel depth. The ratio of ship cross-sectional areas to channel cross-sectional area at the Puget Island site range from 0.09 to 4.50 (blockage factor). Figure 74 is a scale diagram of the bulk carrier "Magnolia" moving through the Columbia channel adjacent to the Puget Island site and illustrates

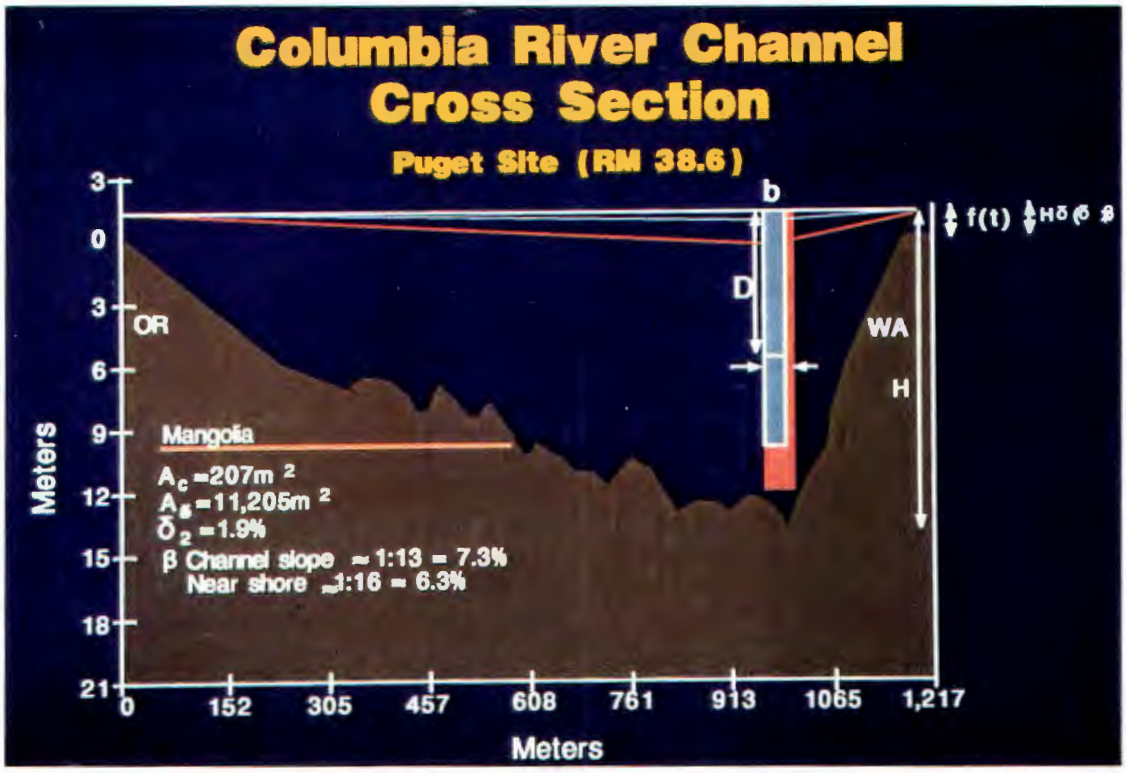


Figure 74. Channel cross-section with ship. Adjacent to Puget Island site with submerged hull of "Magnolia" presented in light blue. The orange rectangle represents the hulls of several of the largest ships observed in the study. Lines associated with drawdowns of each of these ships. Vertical exaggeration is 1:32.

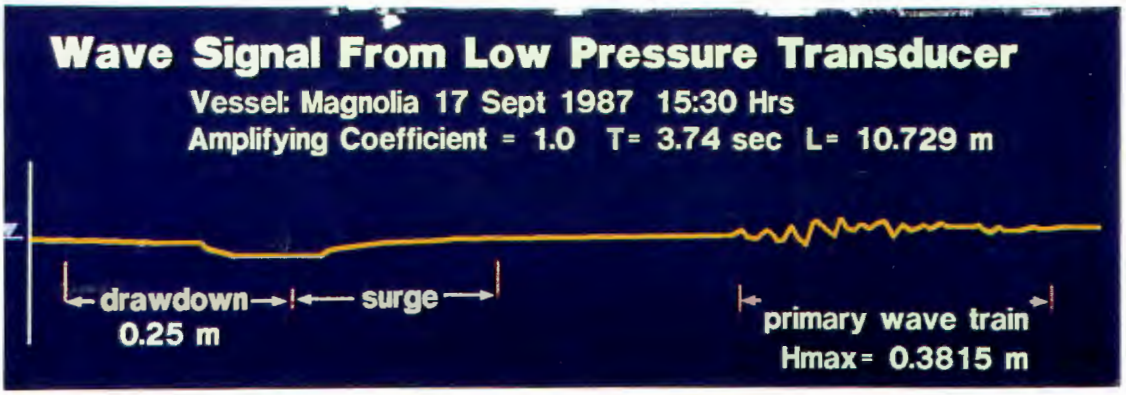


Figure 75. Ship wave record. Ship "Magnolia". Transducer in 1.5 meters of water, ship moving at 12 knots relative to the shore, L = wavelength.

the size ratio of the ships to the navigation channel. The hull outline behind Magnolia's (Figure 74) shows how big some of the ships transiting the lower Columbia get. Figure 75 presents the wave created by the Magnolia, as recorded at the Puget Island site. Figure 76 presents the wave generated by the container vessel Verrazano Bridge. The sequence of events or waves that occur as a ship moves past a site are presented in Figure 77.

The interaction between ship waves and the shore can often be dramatic, as illustrated in Figures 78, 79, 80, and 81, which show the attack of a plunging secondary ship wave near highest high tide at Puget profile PU-9. Appendix C presents other visual examples of ship waves along some of study sites.

Ship wave records (Appendix C) for merchant ships are summarized in Table XX.

Previous work examining the impact of ships waves on shoreline erosion used the analogy that work expended on a shore bank would be directly proportional to the banks erosion; erosion is a function of the work done (Ofuya, 1970). Calculating the rate in which ship waves deliver energy to the shore could allow one to evaluate the erosion along a particular bank. Equation (15) was utilized to calculate the energy in the secondary wave train (Ippen, 1966; Ofuya, 1970):

$$W_s = {}^{20}/S_{max} H_m^2 \; T_m \; Q_s \qquad (15)$$

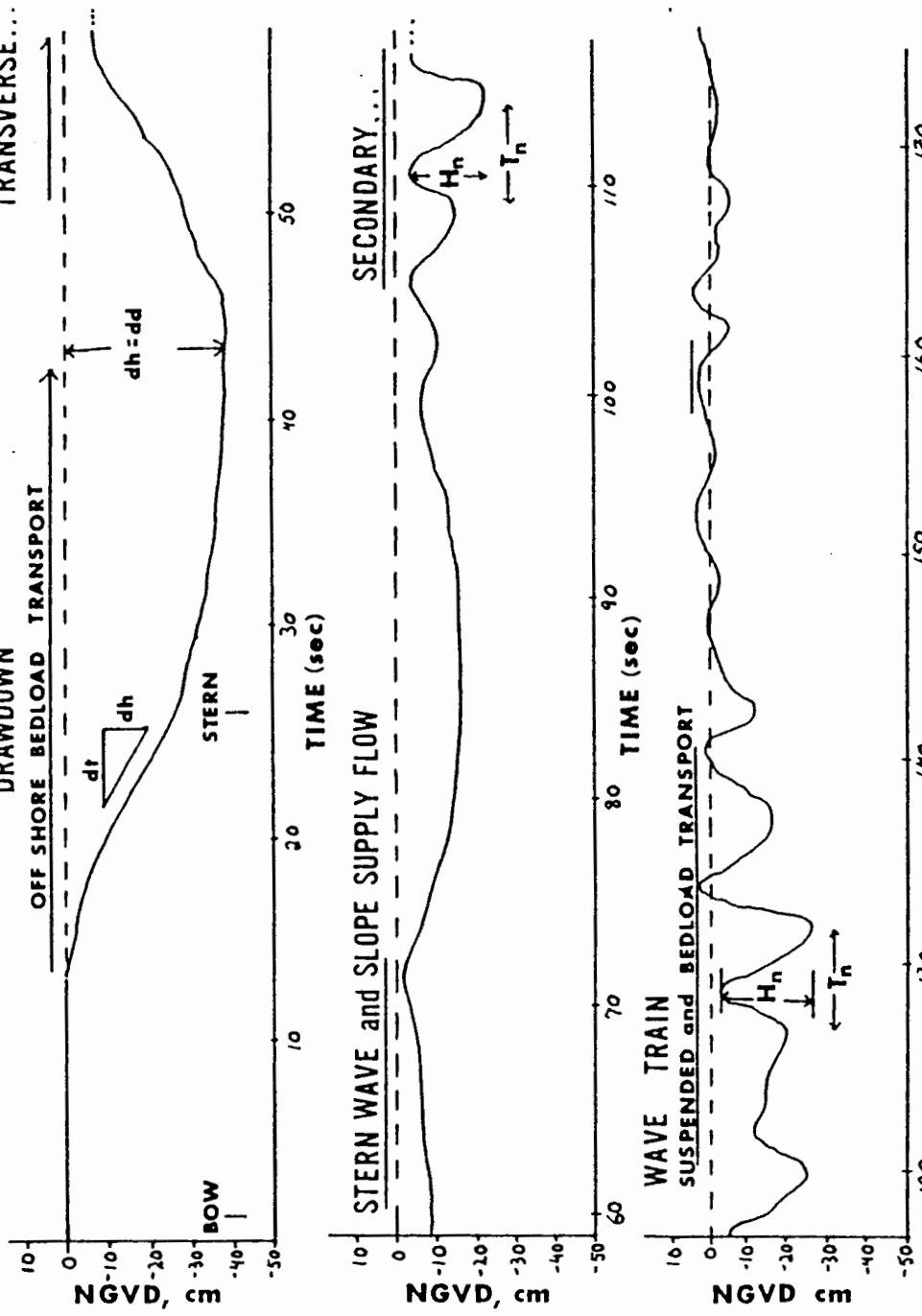


Figure 76. Ship wave. Container ship "Verazzano Bridge", 13JUN88.

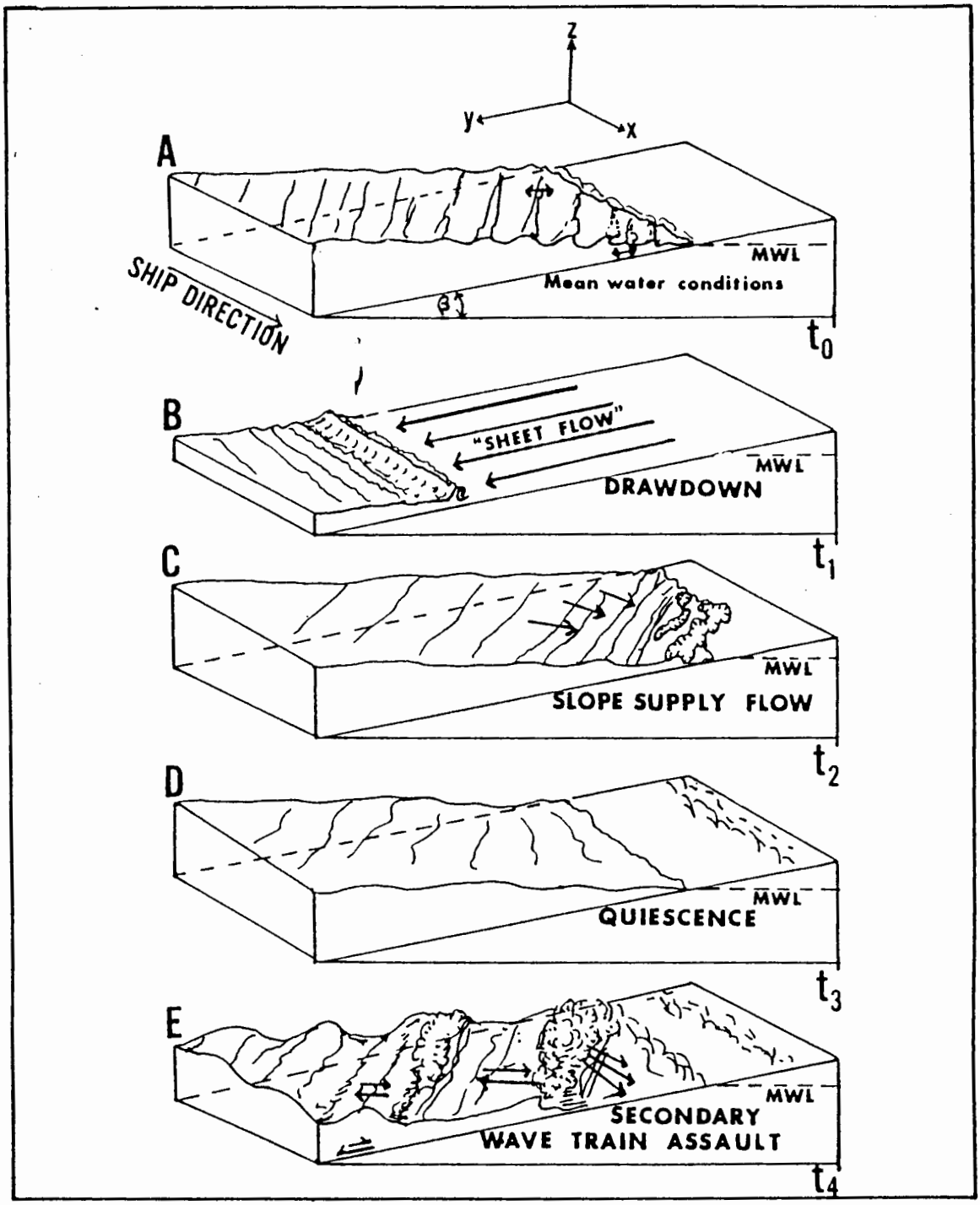


Figure 77. Observed sequence of ship waves. Observed along shores of lower Columbia River.

Figure 78. Plunging breaker (ship wave). Riverward of large beach scarp cut into Puget Island nourishment, 14JUL88.

Figure 79. Wave run-up after breaking. Note turbulence and spray at base of beach scarp.

Figure 80. Wave run-up. Continues with each successive wave.

Figure 81. Beach scarp formation. At end of event we see a distinct scarp has formed at base of the scarp. Puget profile 9, 14JUN88.

TABLE XX

WAVE DESCRIPTION, MERCHANT SHIP PASSAGES

Parameters	Range of Values Observed
mean ship draft	4 - 12m*
ship length.	160.0 - 264.5m**
ship beam...	23.4 - 32.2m**
ship displacement	12,437 - 61,161 tonnes**
V_s.....	5.2 - 8.0m/s
dd.....	27 - 57cm
$H_{max(mea)}$...	8.0 - 38.1cm
T_{max}.....	2.5 - 4.5sec
α.....	0° - 21°
bf.....	.009 - .045
β.....	1:30.0 - 1:13.0
H_b.....	.13 - .47m
d_b.....	.11 - .44m
E_{mq}.....	22 - 539 W/m

* mean drafts as reported from CRPA (1987-88)

** ship dimensions from Lloyd's (1987)

where:

V_s = ship velocity

dd = drawdown; E_{mq} = mean wave energy in Watts/meter

β = beach slope; H_b = height of breaking wave

bf = blockage factor; d_b = depth at breaker line

T_{max} = max. meas. period

$H_{max(mea)}$ = max. measured wave height

α = angle of incident wave on shoreline

where:

W_s = ship wave energy

S_{max} = slope of average maximum power versus energy curve for ship waves 1/sec.

$= 0.038 - (5.05)10^{-6} X_s$

where x_s is the distance from sailing line, $0 < x < 5000$ (feet); for all values of V_s (ship velocity).

H_{max} = average maximum wave height

T_{max} = average maximum wave period

Q_s = rate of ships passing per hour

Based on the average secondary wave trains of fourteen observed merchant ships:

W_t = 241.7 [(ft lbs/hr)/ft shoreline]

= 1,075 [(N m/hr)/m shoreline]

= 0.3 [Watts/m shoreline]

where:

$S_{max} = 0.09 \text{ sec}^{-1}$

$E = \Sigma_1^n H_n^2 T_n^2 = 0.93 \text{ m}^2\text{sec}^2$

$Q_s = 0.42 \text{ hr}^{-1}$

This estimated average work done by secondary ship waves lies within the domain of values derived in Ofuya's (1970) study of navigation channels. The value presented does not account for energy imparted to the shore by the drawdown and transversal stern waves.

SEDIMENT TRANSPORT

Process Delineation and Transport Prediction

The first step in evaluating sediment transport is to define the hydraulic conditions that occur in the study region and which will instigate sediment motion. Once hydraulic conditions are distinguished, the likely range (magnitude) of these is estimated. The processes can then be analyzed by applying established theoretical and empirical relationships to determine the possible extent of sediment transport. Using these hydraulic "transport threshold" relationships, projections can be made of the hydraulic actions likely to have the most impact and those likely to have little or no impact. These projections will be compared to actual field measurements. Finally boundary conditions will be established for a descriptive model of the system.

The threshold of particle movement under a unidirectional current can be predicted using criteria presented by several authors (Shields, 1936; Hjulstrom, 1939; Yalin, 1972; Miller and others, 1977). Table XXII presents velocities needed to create sufficient shear stress to mobilize sediment grains (in Macdonald, 1983), as based on horizontal drag forces and critical drag forces due to eddies in the flow (Goncharov, 1938).

TABLE XXI

CRITICAL UNIDIRECTIONAL FLOW VELOCITIES

Average Particle diameter (mm)	Velocity (m/s)
0.10	0.27
0.25	0.31
0.50	0.36
1.00	0.45
2.50	0.65
5.00	0.85
10.00	1.00

Shields' parameter (Shields, 1936) has been a commonly used measure of sediment motion in fluvial hydraulics. Shield's parameter is a ratio of the driving (shear forces) to the stabilizing (gravity forces). If the forces acting on a sediment grain are examined instantaneously, then Shield's approach is also valid for oscillatory flow (Madsen and Grant, 1975).

Effect of Tidal/River Currents

Currents driven by the tide and river discharge are modeled as unidirectional flows. The Hjulstrom curve presented in Figure 81 can be used to evaluate the approximate current necessary to move standard quartz grains (specific gravity of 2.65). Velocities at the Puget Island site were evaluated using a surface floater.

The surface velocity of a river by theory is greater than that found at the bed (Bagnold, 1966; Streeter and Wylie, 1979), thus it is assumed near bed velocities would be below those found at the surface.

Peak surface velocities observed during maximum ebb current on June 8, 1988 (month of maximum discharge for Columbia in 1988) were about 35 cm/sec where depth was 138 cm; up to 21 cm/sec where depth was 95 cm; and 19 cm/sec where depth was 70 cm. These surface velocities would generate the shear sufficient to instigate motion, but are low enough that near-bed velocities would have little impact. Hydraulic studies and Price meter data collected by the Portland District of the U.S. Army Corps of Engineers in the lower Columbia suggest that the near bed velocities associated with the above surface velocities would be found to fall below the needed threshold velocity of about 15-20 cm/sec. In depths less than 1.5 meters, tidal and river currents have a minimal potential for sediment transport. Further evidence for this is found in sedimentary structures. In depths of 1.5 meters or greater, asymmetrical current ripples were often observed forming in the direction of flow. These are very distinct from the smaller oscillatory wave ripples found in depths less than 1.5 meters that form from wind waves.

Sediment volumes moved during diurnal ebb currents must be evaluated to make conclusions on the relative

importance of each major sediment transport process. An array of three sediment traps were aligned normal to the shoreline to sample peak ebb flow transport during a time in which no ships passed the site. The traps were in the water for 10 minutes on June 14, 1988. The surface velocity of the river was 27.5 cm/sec at the deepest sample trap location. Measured transport increased with distance from the shoreline. Each of the trap arrays suggested all sediment transport occurred as bedload. To extrapolate this measured flux to an annual rate, it was assumed that flow conditions necessary to generate the conditions measured exist for 6 hours per day for 365 days a year. Such conditions probably rarely exceed 6 hours per day (USACE, 1988). Table XXIII presented the measured fluxes at the Puget Island site.

Using the values in Table XXIII, a bed width of 11 meters was used to extrapolate annual flux, derived using the existing beach slope, θ, and the zone from a depth of 0.9 m to 1.5 m.

The estimate of sediment transport rate was calculated in the following method, where a nearshore cell of active transport was derived based on recorded data and observations:

$\theta = 3^{\circ}$

$(2.0/\tan \theta) - (0.9/\tan \theta) = 21$ meters

(.006 kg/m*min)(60min/hr*8hr/day*365day/year)

TABLE XXII

RIVER-TIDAL SEDIMENT TRANSPORT

During Ebb Flow, 11:10-11:22 14JUN88

45 minutes after low low tide
NGVD = 0.57m
Surface water velocity = 27.5 cm/s in depth of 122cm

Estimate of sediment flux

Depth	Sediment Flux
0.73m	0.000 kg/m*min
0.94m	0.003 kg/m*min
1.19m	0.006 kg/m*min

= 788.4 kg/(yr*unit length(m)) * 21 m

= 16,556 kg/yr

= 11.8 m^3/yr

A volume of 11.8 cubic meters per year was extrapolated using the simple, static conditions represented by those measured for a one year period. No dynamic changes were accounted for in this derivation. The boundaries of the cell of sediment transport were based on the depth of initial sand movement as measured by trap and the deepwater edge of the shallow water zone defined in this study. The river discharge during this sampling was above the annual mean for 1988, but almost one half that during May of 1987. This is a source of potential error, for times of high discharge correspond to times of greatest sediment transport. Anomalous high discharges, such as flood events

can account for more than 80 percent of annual sediment transport in rivers (Dyer, 1986). Even though these anomalous events have been dampened by human modifications, flood events greater than 300,000 cubic feet per second (8495 m^3/s), begin to instigate the majority of bedload transport in the lower Columbia River (Beeman, 1985a, b; USACE, 1986).

Effect of Ship Drawdown Wave

Drawdown from ship waves can be used to estimate the magnitude of sheet (plane of water moving downslope) flow down the shore face. Equation (16) was used to estimate maximum near-bed velocities during the drawdown:

$$V_{DD} = (DD_{mea}/\sin \beta)/t_{DD} \quad [L/T] \qquad (16)$$

where:

V_{DD} = velocity of water moving offshore during drawdown event

DD_{mea} = measured drawdown (cm)

β = shore slope (on which DD occurs)

t_{DD} = time of drawdown event

The velocity of water moving down the beach, V_{DD}, can be compared to threshold conditions, or bed shear, was significant enough to move the sand grains, simply by plotting on Hjulstrom's curve. Drawdown velocities were found to range from 0.0 to 70 cm/sec, thus at times they

surpass the critical (point of movement) sediment threshold velocity, as suggested by observations and video records.

Predictions of near-bed velocities can be calculated using linear wave theory, treating the drawdown event as a large period wave. Even a small drawdown of 8 cm and period of 22.4 seconds at a depth of 1.5 meters on a 1:10 slope there is a near-bed orbital velocity, u_o, of 24 cm/s; a velocity sufficient to begin to move some of the sand. It is apparent that the long period drawdown wave generates orbital velocities which can instigate sediment motion in relatively deep water, as presented in Table XXIII.

The passage of a ship can generate a surge (commonly associated with the transverse stern wave) that acts as a turbulent bore front and is often visually observed to entrain sand. This bore moves with a celerity (wave form velocity) far in excess of orbital velocities. Transverse ship waves have a celerity equal to the ship's velocity in deepwater.

Effect of Secondary Ship Waves

Linear wave theory suggests that the secondary waves generated by ships can generate near-bed orbital velocities well in excess of the threshold conditions of the Columbia River sand. Table XXIV presents an example linear wave prediction based on the maximum secondary wave, H_{max} of the ship Veranzano Bridge (13JUN88).

TABLE XXIII

PREDICTED THRESHOLD VELOCITIES AND DEPTHS

Lower Columbia River Sand, D_{50} = 0.3mm
Linear Wave Theory, Drawdown Wave Range

Wave Period, T (sec)	Wave Height (cm)	Depth (cm)	Threshold orbital velocity (cm/s)
20	5	8.1	27.5
20	10	32.4	27.5
20	15	72.7	27.5
20	20	128.8	27.5
20	25	200.3	27.5
20	30	286.7	27.5
20	35	387.6	27.5
20	40	502.3	27.5
20	45	630.1	27.5
20	50	770.4	27.5
40	10	20.5	34.6
40	15	46.0	34.6
40	20	81.7	34.6
40	25	127.6	34.6
40	30	183.6	34.6
40	35	249.6	34.6
40	40	325.6	34.6
40	45	411.5	34.6
40	50	507.2	34.6
60	10	15.6	39.6
60	15	35.1	39.6

TABLE XXIII

PREDICTED THRESHOLD VELOCITIES AND DEPTHS
(Continued)

Lower Columbia River Sand, D_{50} = 0.3mm
Linear Wave Theory, Drawdown Wave Range

Wave Period, T (sec)	Wave Height (cm)	Depth (cm)	Threshold orbital velocity (cm/s)
60	20	62.4	39.6
60	25	97.5	39.6
60	30	140.4	39.6
60	35	191.0	39.6
60	40	249.4	39.6
60	45	315.4	39.6
60	50	389.2	39.6

TABLE XXIV

LINEAR WAVE PREDICTIONS

Given

H_{max} (measured) = 42cm

T_{max} = 4.6sec

α (wave incidence) = 10°

d_{mea} (depth measured) = 1.5m

β (shore slope) = 0.10

Calculated

H_o (deep water wave height) = 41cm

T_o (deep water wave period) = 4.6sec

L_o = 33m

α = 20.2°

TABLE XXIV

LINEAR WAVE PREDICTIONS
(Continued)

C	= 7.2 m/s
H_b (breaker height)	= 54cm
d_b (breaker depth)	= 43cm
L_b (wavelength at breaking)	= 9.3m
α	= 5.6°
C	= 1.98 m/s
u_o (orbital velocity near bed at breaking)	= 163 cm/s
u_o (at d=3.0m)	= 87 cm/s
u_o (at d=6.1m)	= 58 cm/s
u_o (at d=9.1m)	= 38 cm/s

(USACE, 1985)

Sediment threshold predictions under waves were also made using a program modified from one written by Komar and Miller (1975). Table XXV presents program output using the mean grain density, the mean grain size, and the range of wave sizes observed at the Puget Island study site.

Sediment transport by ship waves measured at the Puget Island site is presented in Appendix D.

Table XXV illustrates that higher period waves need a higher near-bed orbital velocity to reach the grains' threshold of motion, but that for the same depth water, a higher period wave generates a higher near-bed velocity.

TABLE XXV

PREDICTED THRESHOLD VELOCITIES AND DEPTHS FOR LOWER COLUMBIA RIVER SAND

grain density =2.6g/cm^3, D_{50} = 0.3mm
Linear Wave Theory, Secondary Wave Range

Wave Period, T (sec)	Wave Height (cm)	Depth (cm)	Threshold orbital velocity (cm/s)
3.0	10	86.9	14.6
3.0	15	154.2	14.6
3.0	20	212.5	14.6
3.0	25	263.1	14.6
3.0	30	306.1	14.6
3.0	35	343.0	14.6
3.0	40	375.1	14.6
3.0	45	403.3	14.6
3.5	10	85.2	15.4
3.5	15	158.0	15.4
3.5	20	230.8	15.4
3.5	25	294.5	15.4
3.5	30	350.8	15.4
3.5	40	400.1	15.4
3.5	45	443.4	15.4
3.5	50	481.9	15.4
4.0	10	82.2	16.1
4.0	15	159.7	16.1
4.0	20	237.2	16.1
4.0	25	317.4	16.1
4.0	30	386.3	16.1

TABLE XXV

PREDICTED THRESHOLD VELOCITIES AND DEPTHS FOR LOWER COLUMBIA RIVER SAND (Continued)

grain density =2.6g/cm^3, D_{50} = 0.3mm
Linear Wave Theory, Secondary Wave Range

Wave Period, T (sec)	Wave Height (cm)	Depth (cm)	Threshold orbital velocity (cm/s)
4.0	35	448.3	16.1
4.0	40	503.8	16.1
4.0	45	553.5	16.1
4.0	50	598.3	16.1
4.5	10	78.8	16.7
4.5	15	158.0	16.7
4.5	20	244.6	16.7
4.5	25	335.4	16.7
4.5	30	413.5	16.7
4.5	35	487.5	16.7
4.5	40	555.2	16.7
4.5	45	616.8	16.7
4.5	50	672.8	16.7

Table XXV also shows us that higher period waves begin to "feel" the bottom in deeper water than lower period waves, given the same wave height. These predictions of the maximum depths of motion help to establish boundary limits when constructing a model of sediment transport in the nearshore zone by waves. Using the wave parameters of T_{max}=

3.76 and H_{max}= 25cm for the observations of this study, the maximum depth at which grains begin to move is approximately three meters. Thus, the 3 meter depth could be modeled as the boundary at which sediment flux is zero.

Equation (17) defines the threshold condition for sand motion:

$$u_{max(-d)} = [8\ (\delta_s/\delta-1)\ g\ D_{50}\ ]^{0.5} \quad (17)$$

$$= [8((2.65/1.026)-1)(9.81)(.0003)]^{0.5}$$

$$= 19.3 \text{ cm/sec}$$

Thus, for the mean grain size of the lower Columbia River sands in the Puget Island region, a near-bed velocity of 19.3 cm/sec is necessary to move the sand, a velocity close to those presented by Hjulstrom's curve.

Figure 82 presents a graph of sediment threshold prediction using small amplitude wave theory. The maximum depth of sediment motion is plotted as a function of wave heights (in the domain of values observed) and wavelengths in Figure 82.

The maximum depth of sediment (of mean grain size, D_{50}) entrainment under the actions of water waves of the range observed at the Puget Island site, with a period of 3.5 seconds, wavelengths between 7 and 21 meters and wave heights between 10 and 60cm range from about 0.5m to 6m. The most common waves had heights between 0.2 and 0.3 meters and wavelengths between 7 and 11 meters, which begin to move sediment in depths less than 2 meters. Using the

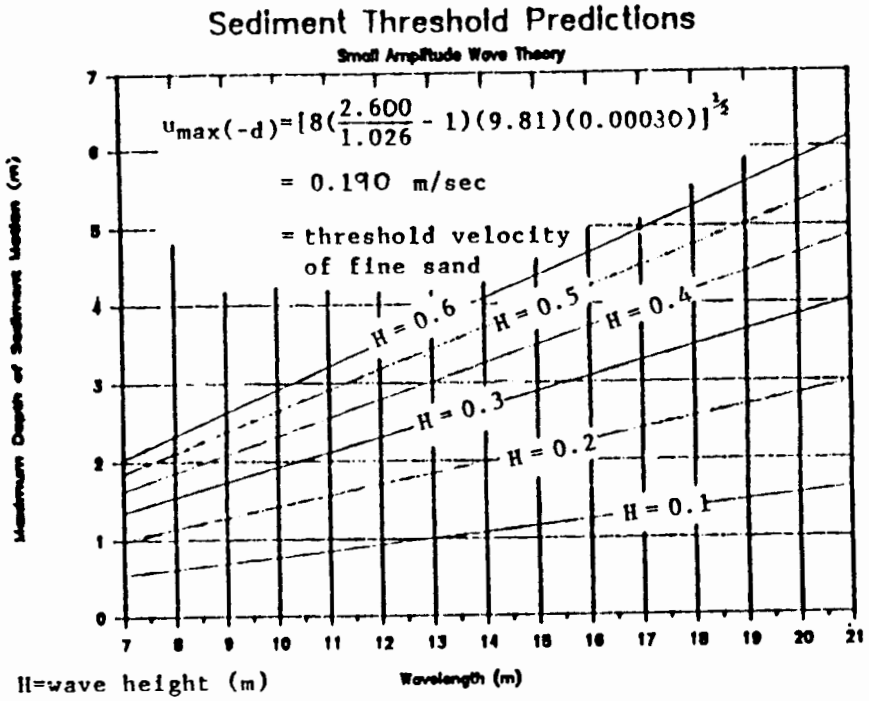


Figure 82. Estimating sediment motion. Effect of water waves using small amplitude linear wave theory (USACE, 1984).

mean observed wave height of 25 cm and wavelengths of about 14 m, sediment motion can be at a maximum water depth of 2 meters. These estimates offer a means to establish a riverward boundary condition of sediment motion for a near-shore shallow water sediment transport model.

The presence of sand in the sediment traps showed consistently that wave orbital velocities were sufficient to move sand. Point sampling with a array of sediment traps measured cumulative sediment flux for some time, t, at 2 depths for transport; parallel to the shoreline (longshore component) and perpendicular to the shoreline

(on and offshore components). Table XXVI presents an example of transport measured for a upstream passage (Magnolia, 17SEPT87). Note that at depths of 48 cm, outside the breaker zone, sand moves both on- and offshore, but that the offshore component of transport exceeds that moving onshore. This is consistent with most of the ship wave sediment transport observed, suggesting a net erosion of the beach face.

Longshore Currents by Secondary Ship Waves

Longshore currents are those that move parallel to a shoreline and which are for significant sand transport in many coastal settings (Komar, 1976). At the Puget Island site longshore currents generated by ship waves, such as that observed during the passage of the ship Magnolia on September 17, 1987 (Table XXVI), can result in the most sediment moved at a single point in the nearshore zone, but because longshore currents are limited to a relatively narrow zone of about 5-10 meters perpendicular to the shoreline, they may not move the most sediment in a beach cell (section of beach). It was clear from reviewing of aerial imagery of the Puget Island site over the last fifty years, during which time the accretionary lobe developed north of the site, that longshore currents, either by: ebb flows, wind waves (little evidence), or ship waves or a

TABLE XXVI

SEDIMENT TRANSPORT DATA COLLECTED BY SHALLOW WATER SEDIMENT TRAP ARRAY FOR THE UPSTREAM PASSAGE OF THE BULK CARRIER, MAGNOLIA, 17SEPT87

Longshore transport was zero in the downstream Direction, LONG = upstream longshore transport ON=onshore OFF=offshore

Water Depth (cm)	Sample Depth (cm)	Sediment Transport Dry Weight in Grams			Mean Settling Velocity (cm/s)		
		ON	OFF	LONG	ON	OFF	LONG
20	Bed	5.1	31.4	186.0	3.2	3.6	3.3
20	9.5	1.0	13.9	117.7	3.0	3.2	3.2
20	17.1	0.1	4.4	74.5	2.9	3.2	3.5
48	Bed	26.1	36.0	-	3.9	3.5	-
48	9.5	4.0	5.4	-	3.2	3.2	-
48	17.1	1.8	3.0	-	3.2	3.2	-

combination are responsible for significant sediment transport.

Longshore currents generated by waves on a beach have been extensively investigated by several researchers: Longuet-Higgins, 1970a, 1971; Longuet-Higgins and Steward, 1962, 1964; Komar, 1975, 1979; Komar and Inman, 1970; Galvin, 1972b; Galvin and Eagleson, 1965. The research of these authors and others has resulted in the derivation of analytical and empirical solutions for estimating longshore currents.

The most important variable controlling longshore currents for a given set of wave heights and period is the

angle of incidence at which the wave fronts attack the shoreline (oblique-wave approach). The longshore current is produced by wave set-up, edge waves, and oblique-wave approach. An empirical derivation of longshore current was presented by Komar and Inman (1970) in Equation (18):

$$v_l = 2.7\ u_m \sin \Theta_B \cos \Theta_B \qquad (18)$$

Equation (18) gives a maximum longshore velocity, v_l, at Θ_B = 45 degrees.

where: u_{max} = maximum orbital velocity at breaking point

$$= [(2E_B)/H_B]^{0.5} \qquad (19)$$

H_B = wave height at breaking

E_B = wave energy at breaking

Θ_B = wave incidence at breaking

Komar (1975) presented Equation (20) in which longshore velocity can be derived based only on the breaking wave height and wave incidence at breaking:

$$v_l = 1.17(gH_B)^{0.5} \sin \Theta_B \cos \Theta_B \qquad (20)$$

Figure 83 presents a plot of the estimated longshore current derived using Equation (20); with a range of wave heights and incident angles. The domain of values observed at the Puget Island site include: wave heights from 10 to 50 cm and incident angles from 0 to 21 degrees. Waves with an incidence of 10 or more degrees that surpass the sediment threshold velocity and would be expected to move sand. Sediment trap data and visual observation showed that increased incidence of the waves increased the shore

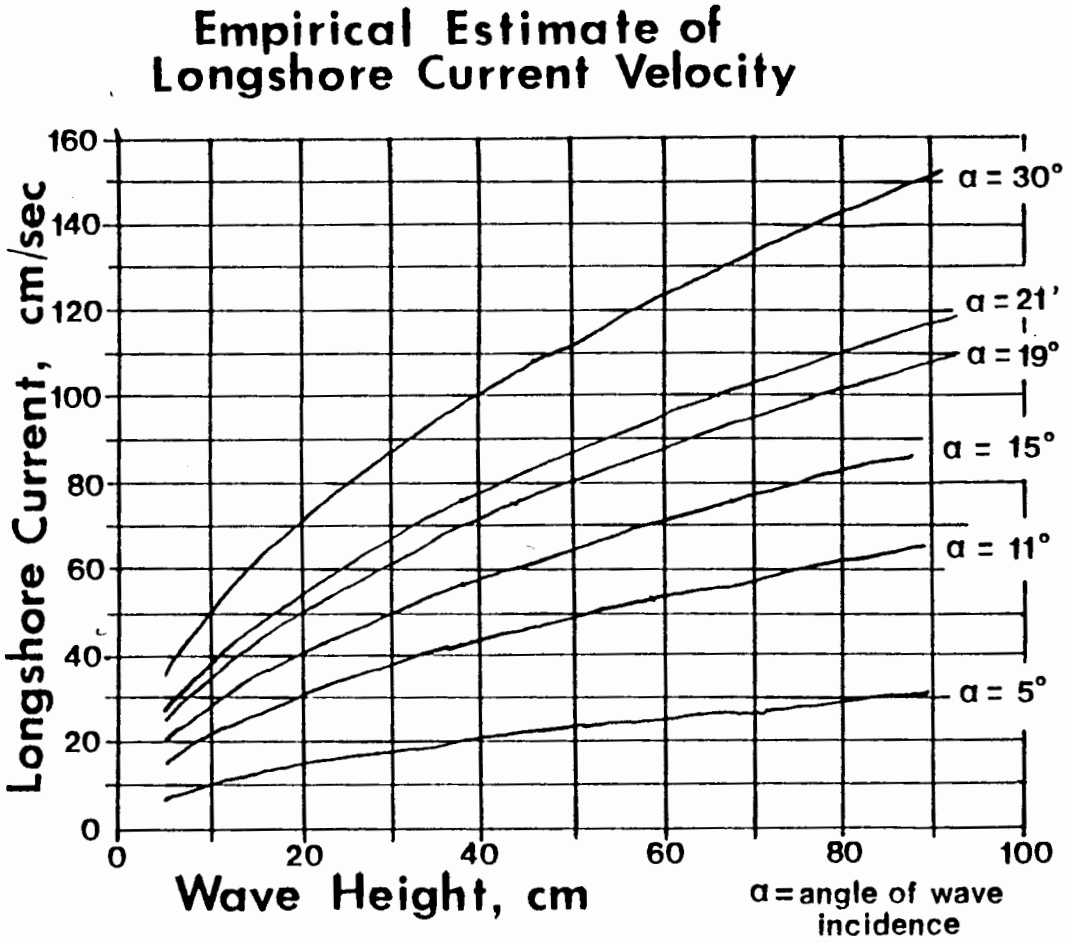


Figure 83. Predicted longshore current velocities, as estimated by Equation (20) (Komar, 1975).

transport. Waves with an incidence of 5 degrees or less had little to no longshore transport component as measured by trap.

Muir Wood and Fleming (1981, p.122) present a method to calculate the longshore velocity distribution in the surf zone. A short BASIC program was written using the technique and Figure 84 graphs the results after entering representative ship wave data into the program. Figure 84

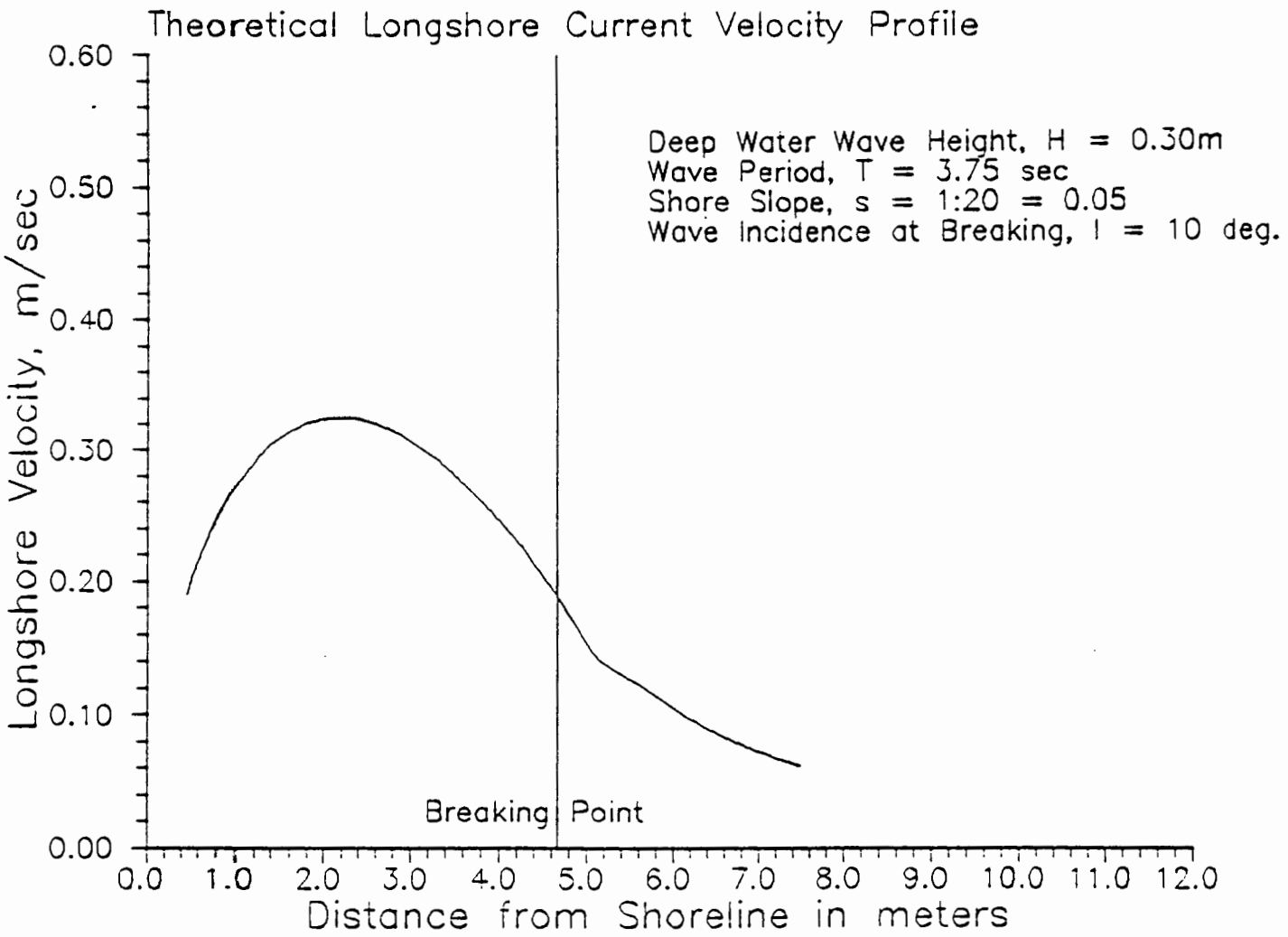


Figure 84. Predicted longshore current distribution through the surf zone. Using BASIC program based on analytical solution presented by MuirWood and Fleming (1981).

illustrates the range of longshore current velocity through the surf zone and the zone in which sediment transport is most likely to occur. Using data representative of observations at the Puget Island site, this analytical solution (Muir Wood and Fleming, 1981) produced velocities great enough that transport would be expected for incident wave angles of 8 degrees or more in the surf zone. These derivations allow limits or boundaries to be estimated for a zone or corridor of longshore sediment transport.

Field Sampling

The results of the sediment trap array system show distinct components of sediment transport in shallow water zones along the lower Columbia River (Appendix D).

The processes instigating sediment transport in the near-shore zone during the passage of a large vessel in the Columbia are illustrated in Figure 85, a time-sequential cartoon of the processes. This set of processes move as a group along the river bank at approximately the same velocity as the ship. The processes are similar to the sequence listed in the Table IV. To better understand this set of processes, they are examined as individual actions, and then modeled by using existing theory of analogous processes common in the coastal environment. The primary difference between ship waves and those waves that have been studied in theory and coastal environments is the time

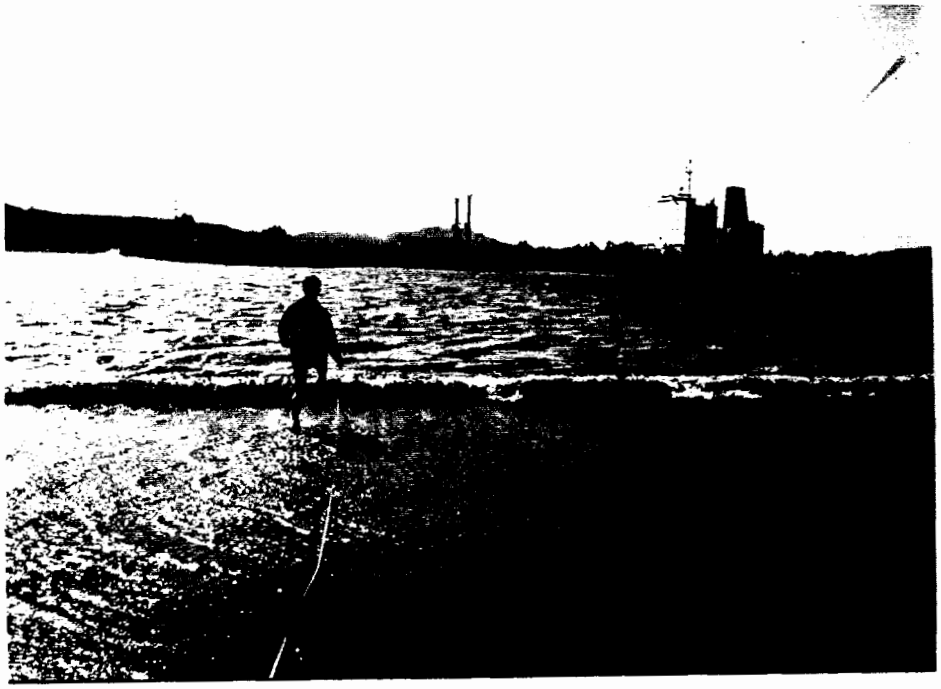


Figure 85. Ship drawdown wave. Sheet flow off the shore slope. Bulk carrier "Coast Range."

dimension and the distribution of wave forms in the set of waves. Wave sets for a given time period in theoretical and natural settings tend to be modeled as a group of individuals with similar dimensions, whereas ship waves are a set of distinctly different waves. Separating the ship waves out into distinct subsets, evaluation by analogy provides a means of analyzing the interaction between ship waves and a shore slope.

The distinct subsets of ship waves observed at the study sites are as follows:

The first action that occurs on the shore is the drawdown wave, a rapid removal of water off the shore when

the ship is approximately normal to the shoreline. As a ship "pulls" itself through the water with its screw (propeller), similar to a screw driven into wood, the ship pushes up a mound of water in front of its bow. This bow wave increases in size as the ship increases its speed (Constantine, 1960, 1961) and the water surface around the ship drops relative to the surrounding mean water level, bringing the ship closer to the bed of the channel. The phenomenon in which the ship's keel approaches the channel bed with increasing speeds is called "ship squat" and is believed to be the driving mechanism behind the drawdown that occurs at the shoreline. The depression in the water surface around the ship creates a head differential with the surrounding water and thus water moves toward that low. The greater the ship squat and the closer to shore the ship, the greater the drawdown wave will be. One of the most detailed analyses and empirical solutions of ship squat was done by Barrass (1979). Barrass's method was used to predict squat for the observed ships during this study. Barrass (1979) found that squat is primarily a function of speed, but is also dependent on channel cross-sectional area and mid-ship cross-sectional area of the ship. Figure 3-67 shows the drawdown for the bulk carrier "Coast Range." The drawdown waves had periods of approximately 40-60 seconds and were followed by replacement of the displaced water back onto the shore.

The surge or transverse stern wave that replaced the water back onto the beach face move diagonally up the beach face, in the direction of ship passage. This contrasts with drawdown which moves water directly down-slope. After the transverse stern wave, the water level returns to near mean conditions, "quiescence" in this study.

The last wave event is often the most obvious, the secondary wave train of the ship. This group of waves had an incidence from 0 to 21 degrees upon the shoreline. The secondary wave train most often broke as plunging breakers. Sediment trap data and visual observation showed that the greater the incident angle of these waves, the greater the longshore transport. The angle of incidence is controlled by the shoreline configuration and offshore bathymetry. The river channel nearshore morphology directly controls the manner in which waves refract and thus wave incidence along the shoreline. Figures 86 and 87 illustrate the assault of a plunging secondary ship breaking wave at Puget Island and associated sediment plumes. The sediment plumes are portions of the bed that have been brought into suspension by water particles accelerating under the wave. As the sediment is lifted up into the wave, the faster moving water particles can continue the sediment plume's upward motion. Water mass has a net movement shoreward in shallow water and the breaking wave cascades much of this water momentum toward the shore, carrying the sediment

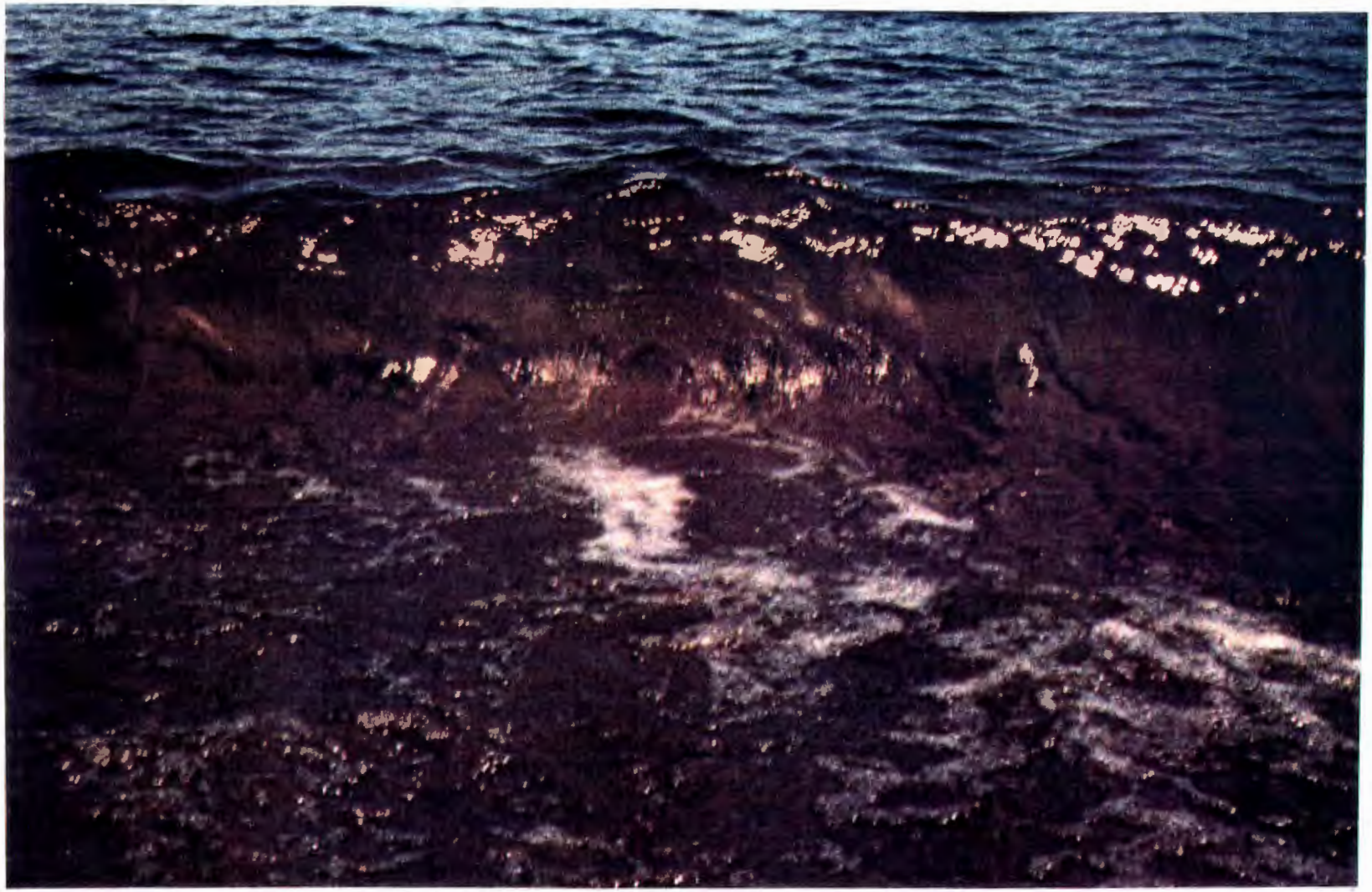


Figure 86. Plunging ship wave. Breaking height of wave is approximately 32 cm, 04AUG88.

Figure 87. Wave breaking in the plunging form, characteristic of most secondary ship waves observed, but spilling, surging, and collapsing breakers were observed. Note "jet" of water in plunging tongue of the wave. Under the assault of a regular train of waves, the jet scours a longshore trough and a longshore bar develops riverward of the plunge line. Most sediment suspension occurs in close to the breaking line.

plume with it. The plunging mass of water scours into the bed, moving more sediment which is subsequently deposited in the lower energy zone just riverward of the plunge line. The water mass moved up the shore after the wave breaks retreats off the shore, carrying sediment with it in a sheet flow action similar to the ship's drawdown.

Sediment flux through the water column at a point was determined using sediment trap data. Each individual trap sediment sample in an array was normalized to mass per unit width and plotted versus the mid-trap elevation above the bed. The three points of each array were then fitted with a exponential line of best fit. This method was chosen because on established sediment distributions above a boundary (Einstein, 1972; Bagnold, 1966; King, 1972). The area under best fit curve was than used to estimate the total sediment quantity moving over a unit width of bed during the event in the measured direction. That sediment quantity moving at that point was then compared with the quantities moving at other measured points. The net motion and distribution of transport in the nearshore zone was used to extrapolate the volume of sand moved along, on, or off the shore.

Figure 88 shows the results of measuring sediment transport during the passage of the bulk carrier "Leandros." The curves show a significant longshore transport component at the point closest to the shoreline,

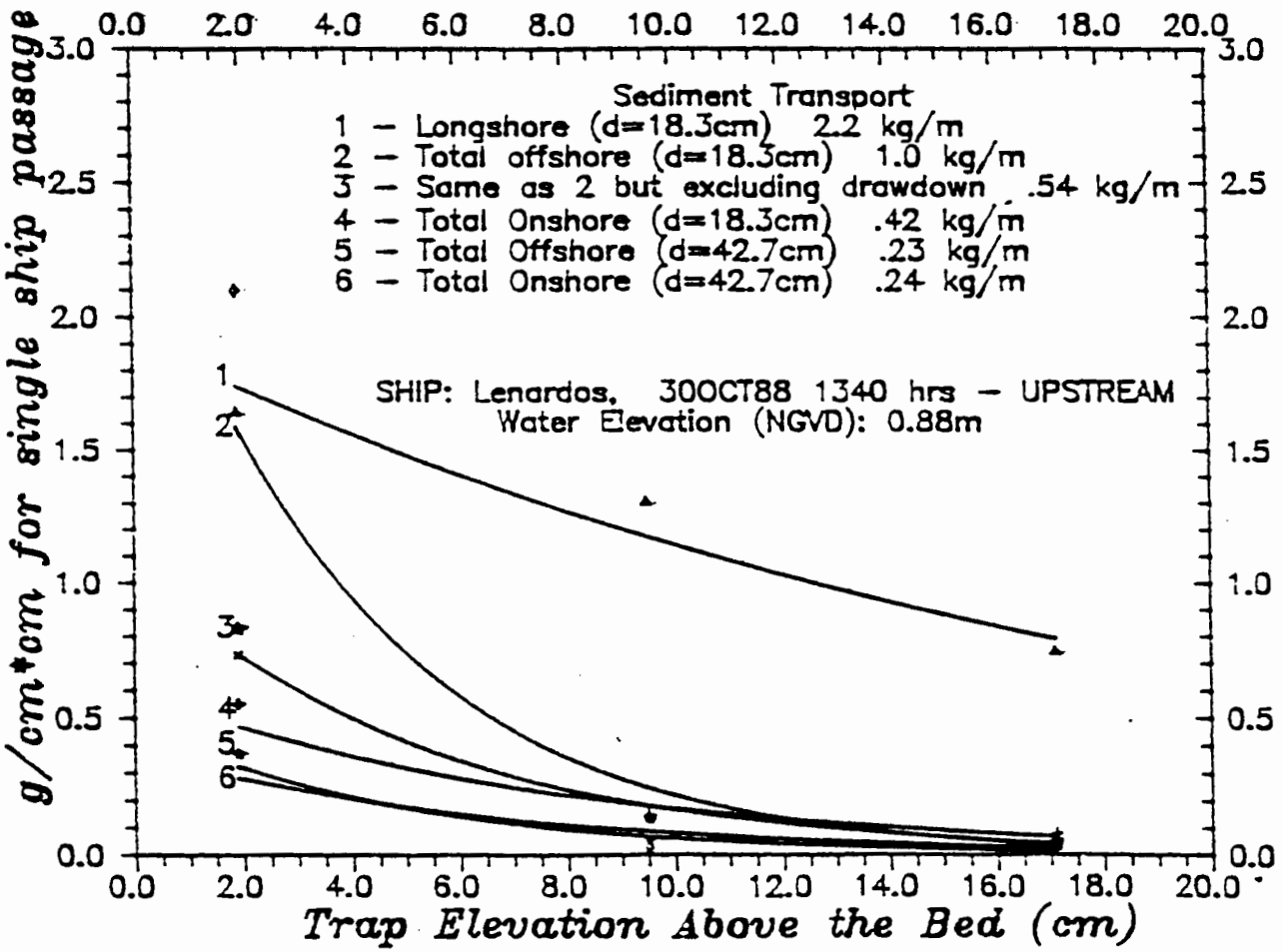


Figure 88. Shallow water sediment transport by the ship waves of "Lenadros." 30OCT87.

in the surf zone. Offshore transport of sand in the surf zone exceeded onshore transport and the drawdown event moved 44% of the total quantity measured offshore. In deeper water where the on-and off-shore components would be expected to be similar due to the oscillatory currents on a wave, it is seen that the two measured quantities are similar.

Figure 89 displays the sediment transport during passage of the bulk carrier "Coast Range." For "Coast Range" offshore transport exceeded onshore transport just outside the surf zone (in a depth of 34 cm). The drawdown event for "Coast Range" was minor, accounting for only 5% of the offshore transport.

Figure 90 presents the results from a large wave trained generated by the U.S. Naval ship "Gray"(#1054). At a depth of 44 cm the waves created an offshore sediment transport of 62.1 kg/m per event and an onshore transport of 24.0 kg/m per event. The ship "Gray" resulted in a net offshore removal of sand of 38.1 kg/m during the event. This data suggests that the high velocity of the Gray, 15.7 knots and resulting H_{max} of 43 cm in 2 meters of water instigated sediment flux far in excess of most sediment transport rates instigated during the passage of observed merchant vessels. The "Gray" did not create a large drawdown because of its small size compared to merchant vessels.

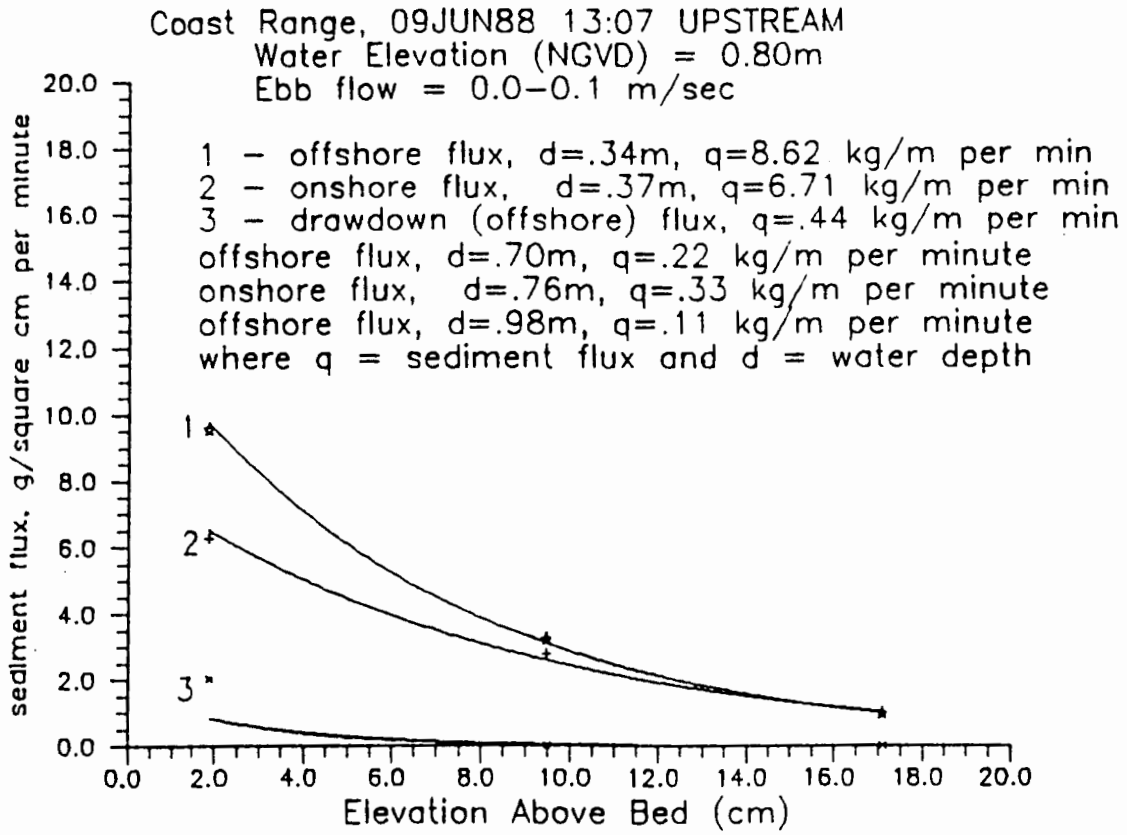


Figure 89. Shallow water sediment transport by the ship waves of "Coast Range." 09JUN88.

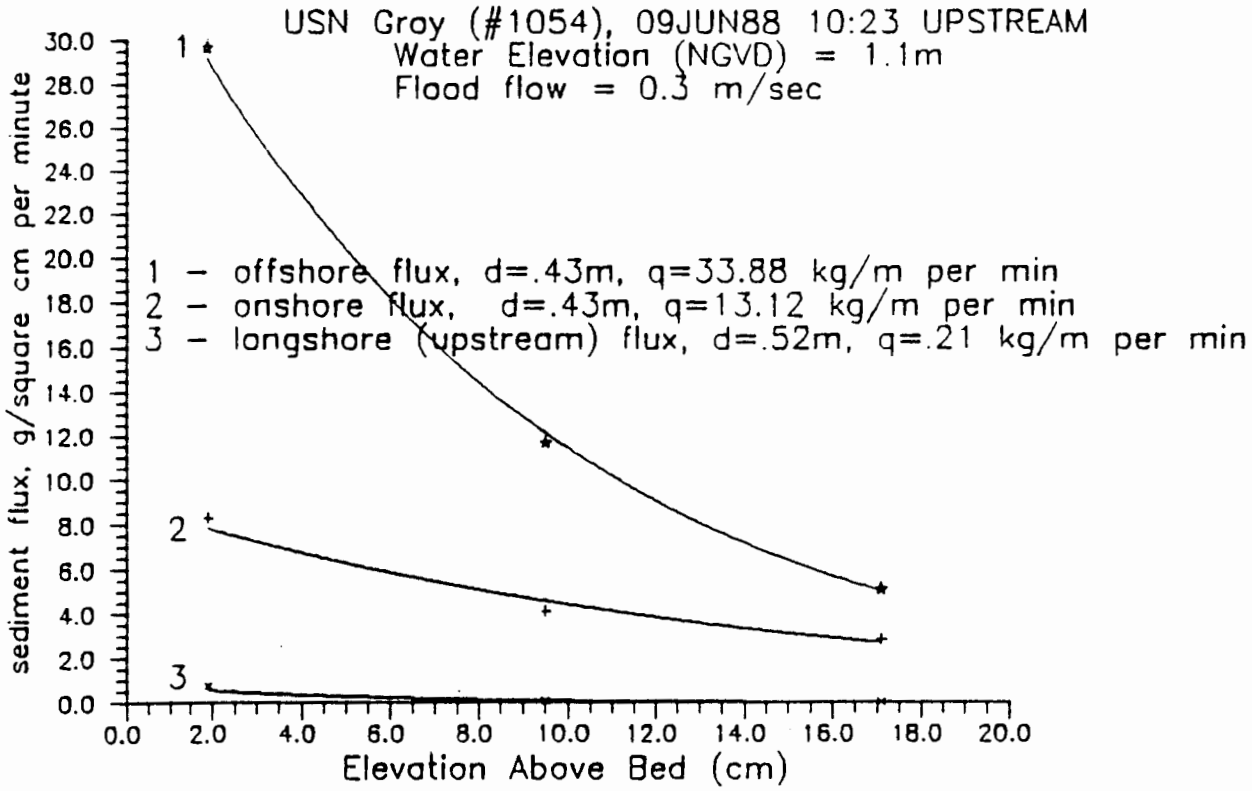


Figure 90. Shallow water sediment transport by the ship waves of the "U.S. Gray". 09JUN88.

Merchant vessels observed had a mean velocity of 12.5 knots, ranging from 10.0 to 14.6 knots (14 ships) and a mean wave height of 21 cm. The naval vessels observed transiting the lower Columbia for the 1988 Rose Festival in Portland, Oregon, had a mean velocity of 14.2 knots and a mean wave height of 29.7 cm. Because the naval vessels are an anomaly, with about a dozen ships transiting the lower Columbia during a 2 to 3 day period twice year (in and outbound passages during the Portland, Oregon Rose Festival in June), the actions of their waves were not used to extrapolate annual transport rates. The erosion caused by the naval ship waves did show what can occur when ships move at higher velocities, as evidenced by the work of Ofuya (1970) and Sorensen and Weggell (1984). Both primary and secondary ship wave heights are proportional to velocity squared (Barrass, 1979; Sorensen and Weggell, 1984; respectively).

The range in magnitude of sediment transport caused by the waves generated by merchant ships are presented in Table XXVII.

Sediment transport distribution across the beach face (perpendicular to the shoreline) was measured for the ship "Coast Range," and found to vary greatly for the points sampled. Figure 91 displays the sediment flux distribution based on the points sampled during the passage of "Coast Range." Sediment flux increases approaching the breaker

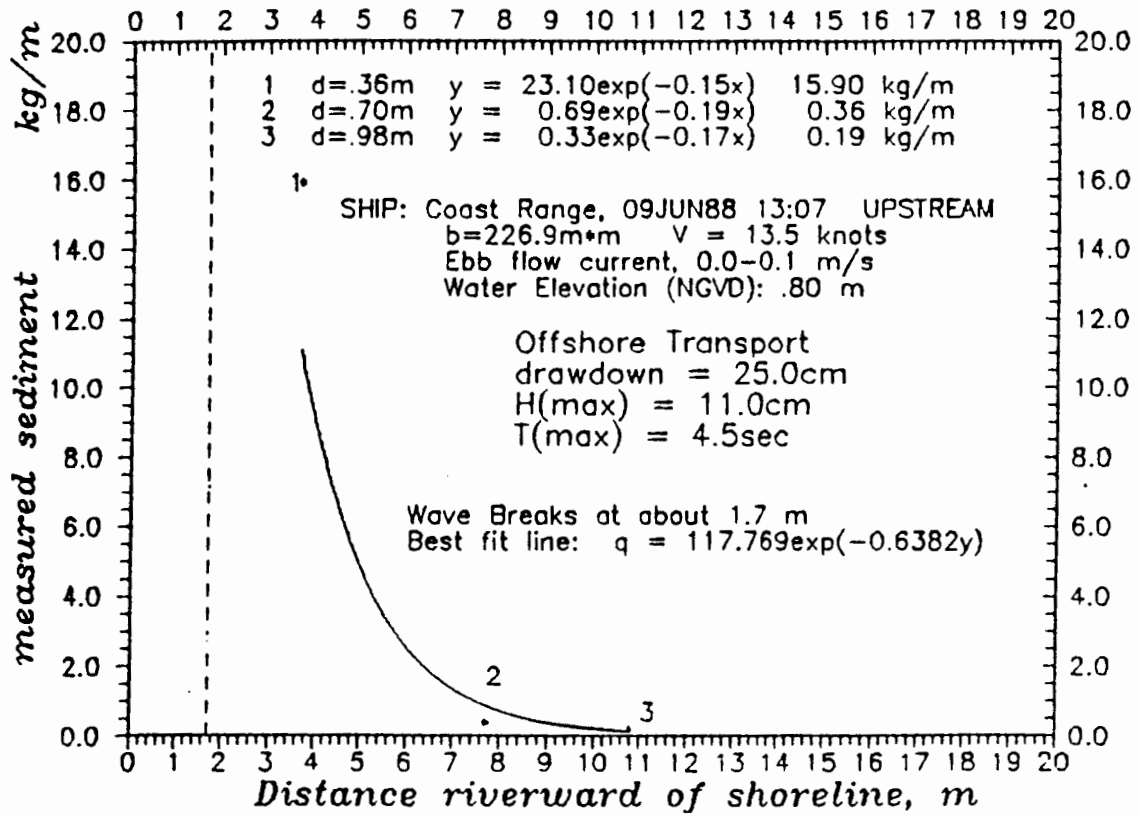


Figure 91. Sediment flux distribution normal to the shoreline for the ship "Coast Range." 09JUN88.

TABLE XXVII

SHALLOW WATER SEDIMENT TRANSPORT BY MERCHANT SHIP WAVES

	Minimum q_{mea} (kg/m)	Maximum q_{mea} (kg/m)	Net flux (m^3)
depth Onshore	.18m = .42	.33m = 12.5	23,397
depth Offshore	.18m = 1.0	.33m = 15.9	29,761
depth Longshore	- = 0.0	.10m = 18.2	

zone. This observation is supported by the work by the Beach Erosion Board (1933; in: King, 1972), that showed an increase in sediment flux and suspension in proximity to the surf zone during ocean wave assault (Figure 92). Using the analogy to previous work (King, 1972) and shallow water sediment trap data, it is suggested that most sand transport by ship waves in the lower Columbia will occur in proximity to the surf zone.

To model sediment transport in the shallow water nearshore zone, sediment trap data was extrapolated in the following manner.

The measured points in the water column were fit with an exponential line of best-fit based on exponential current and sediment transport distributions above a boundary (Bagnold, 1966; Kraus, 1987; King, 1972). This

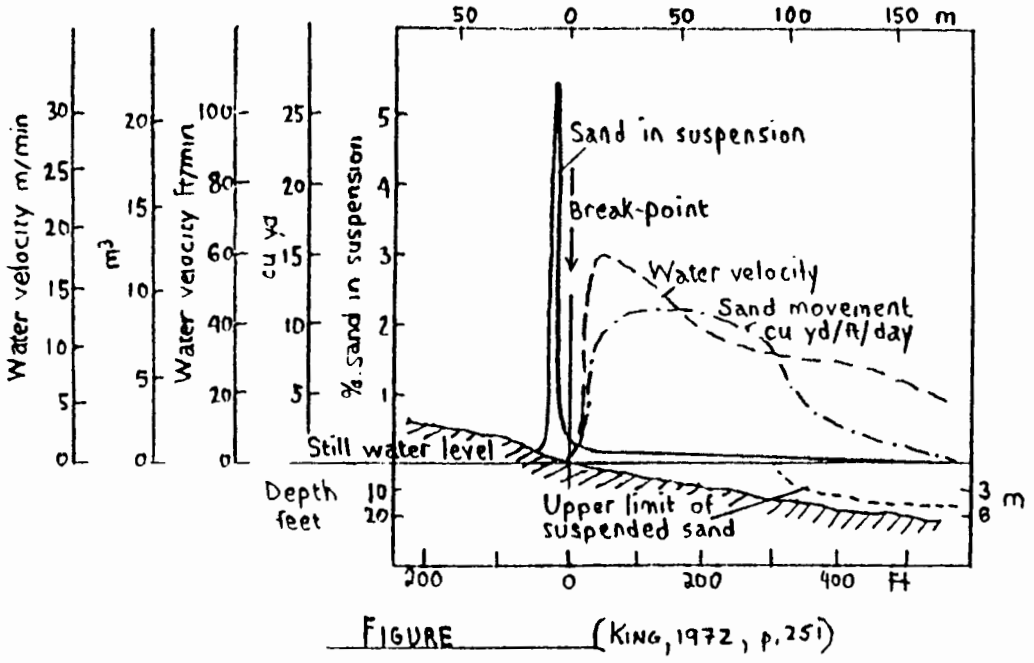
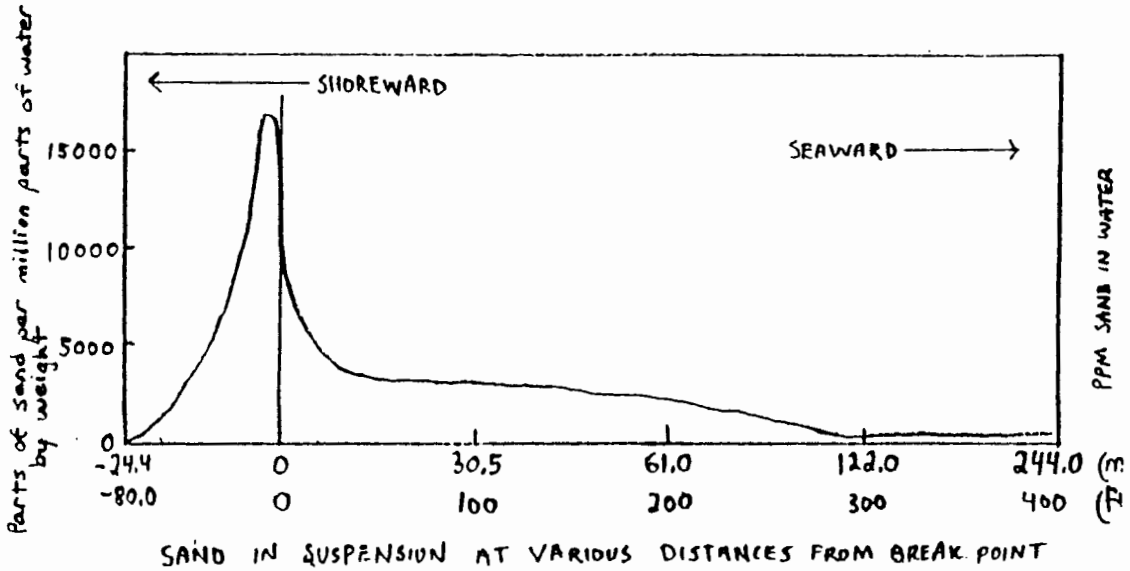


FIGURE (KING, 1972, p.251)



SAND IN SUSPENSION AT VARIOUS DISTANCES FROM BREAK POINT

Figure 92. Results of studies by the Beach Erosion Board, 1933 (in: King, 1972, p.251). Near the wave breaking point, sand is moved in suspension in concentrations of 17,000 ppm (mg/l) by weight. Moving 7.6 meters seaward, this concentration dropped to only 4,000 ppm and at 84 meters it has fallen to 1,000 ppm.

plot was then integrated using the bed and water surface as boundary limits to give an estimate of the total sediment flux at that point. Equation (21) presents the simple integration to determine sediment flux during a single event.

$$q_{mea} = \frac{\int_0^h k_1 * \exp(-k_2 z)\,dz}{10} \quad [kg/m*d_{cm}] \qquad (21)$$

where: h = water depth

q = sediment flux

k_n = constants of integration

z = elevation above the bed

To derive the estimated annual sediment transport rate from the net sediment transport on- or offshore as derived from Equation (21), the quantity was extrapolated for the total number of events during the year, the entire length of the Puget Island beach cell, and divided by the sediment's bulk density. Equation (22) used the annual number of ship passages, the sediment bulk density, and the shore dimensions of the sediment cell in question:

$$M_{mea\text{-}max}[m^3/yr] = \frac{q_{(mea\text{-}max)}[kg/m]}{1{,}400\ [kg/m^3]} * Xb_n[m] * Q_s \qquad (22)$$

where: q = sediment flux

X_b = beach cell length

Q_s = rate of ship passage

M = total estimate of annual sediment flux

Sediment trap data reveals that drawdown only transports sediment along the bed (none in suspension), but can account for about half of the sediment mass moved offshore during the entire set of ship waves.

The relative importance of a ship's displacement within a confined channel can be mathematically represented in the blockage factor, bf. Blockage factor is a measure of the ship hull cross-sectional area's percentage of total channel cross-sectional area (the ship's mid-sectional cross-sectional area divided by the channel cross-sectional area). Brebner and others (1966) suggested that if bf > 1-2% for ships moving at or above an established velocity then the ship drawdown or removal of water off the beach may become the dominant erosive agent. For most merchant ships drafting 6 m and more in the Columbia, the blockage factor ranges from 0.9-4.5% (Abbe, 1988b). Ships observed with blockage factors of .009 caused only slight drawdowns moving at the same or greater velocities (naval frigates) as larger merchant ships with blockage factors of 0.02 or more.

Trap data showed a general trend toward a net offshore sediment flux in water less than 1m in depth. Longshore transport can far exceed onshore and offshore transport components, but was heavily dependent on the wave incidence and shore morphology. When wave incidence became negligible, the longshore transport likewise became

negligible. Field data showed that all longshore transport during ship passage occurs in the direction of ship motion.

A simple geometric model to illustrate hypothetical sediment transport during ship wave assault is presented in Figure 93. The model is based on the sediment flux samples measured by the traps and boundary conditions established from wave parameters and theory. The maximum measured flux, q_{mea}, is used as the maximum flux, q_{mmax}, along the beach, an estimate that is most likely below the real maximum flux, q_{rmax}. Sediment flux done beach slope gradient is greatly simplified in the model as a set of linear functions increasing to some point near the breaker zone and decreasing seaward of some peak position and

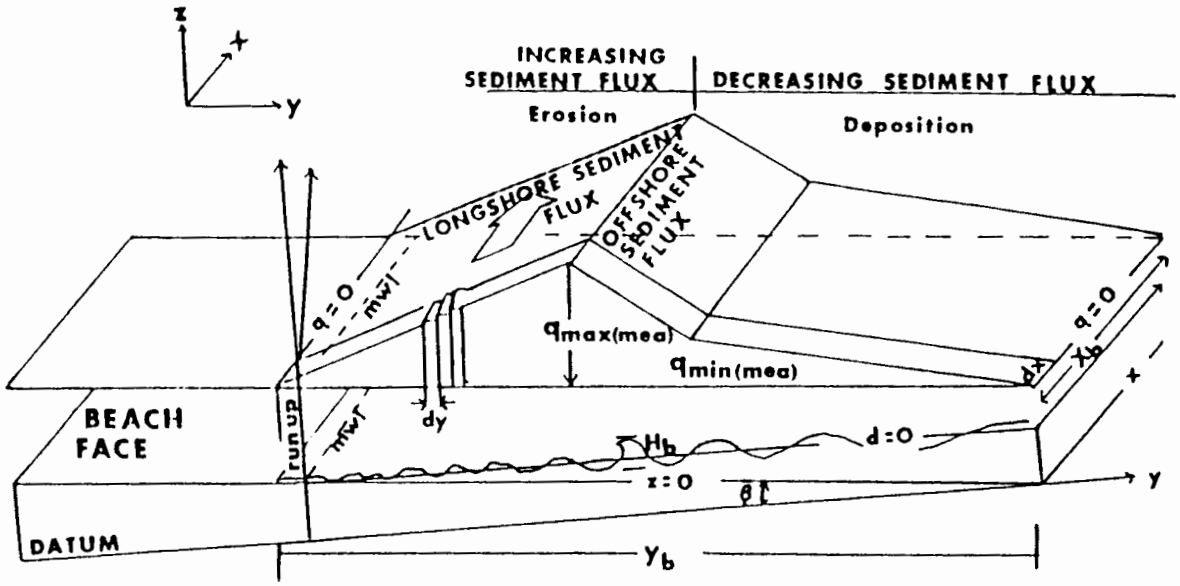


Figure 93. Simple linear model illustrating ship wave sediment transport in shallow water as measured by shallow trap array.

representing the erosion/deposition on the beach face. The model assumptions include:

> no net sediment motion preceding the measured ship wave assault; sediment trap data is representative of the real world system;
>
> the maximum measured sediment flux is close to the real maximum flux for some beach cell, but probably is less than the actual peak flux, q_{rmax} (thus a conservative measure);
>
> the beach is smooth and continuous for the entire cell; the change in water level up and down the beach does not alter the processes that occur, just where they will occur;
>
> the shoreline and bathymetry of the beach cell is linear, thus neglecting wave refraction and localized current amplification or dampening; the data is representative of all ships drafting more than 5.8 meters;
>
> and that the measured sediment transport direction is representative.

The boundary conditions are established using the maximum depth of critical velocities generated by passing waves and the maximum runup onto the beach by these waves.

The offshore sediment flux can be compared to the actual sediment volume changes at the study beach. The total changes in sediment storage along the shore of the study beach to a minimum elevation of approximately -1.0 NGVD (low low water) were computed using 2-D computerized cell changes (Birkemeier, 1988) of field surveys (Abbe, 1989). After the 1987 nourishment at the Puget site, from July 31, 1987 to June 7, 1988 the loss of sand was 26,197 m^3 (Abbe, 1989), about twenty seven percent of the 97,903

m^3 quantity placed at the site during the July 24-29, 1987 nourishment.

The maximum net (ABS[offshore-onshore]) sediment flux component of the trap data suggests that for 3,600 merchant ships (in- and outbound traffic) with drafts of 6 meters or more moving past the Puget Island Site, the generated waves (acting on a smooth beach face) can account for the transport of a minimum sand volume of 1,086 m^3 to a maximum of 6,364 m^3 moved offshore in shallow water. The average duration during which the actions of merchant ship waves act the shoreline is 176 seconds, thus the maximum measured offshore sediment flux is 1.2 kg/m per minute. Because of the exponential distribution of sediment transport through the surf zone, I believe the maximum estimate is well below the actual offshore transport occurring in the surf zone. By examining sediment transport caused by the waves of naval ships, I believe a more representative upper limit of sediment flux out of the beach cell can be estimated. Assuming the impact of the waves generated by a passing naval frigate is representative of all deep draft ship waves during a year, the estimated maximum net transport (using the maximum measured transport during passage of the "US Gray") comes to 73,478 m^3 per year offshore; a value that exceeds the eroded 26,197 m^3 volume of sand at the Puget Island site by 2.8 times. The average duration of naval ship wave actions on a shore was 63 seconds. The "US

Gray" caused a flux of 59.1 kg/m per minute offshore and 22.9 kg/m per minute onshore; a maximum net offshore sediment flux of 36.2 kg/m per minute. These calculations offer a range of sediment transport that encompasses the measured volume of sand that eroded from the Puget Island beach cell.

The model and extrapolations of sediment transport based on measured values suggests erosion transgresses up the beach face and deposition occurs on the lower beach in shallow water depths offshore. The effect is a lowering of beach slope. Profiling showed erosion of the upper beach, deposition in the shallow water depths of the lower beach and an overall lowering of the beach slope.

The net longshore sediment transport component generated by ship waves over time is downstream because of the significant increase in ship drafts on the outbound (downstream) passages, as presented in Figure 94. It is a conclusion that there is a definite longshore and offshore transport of sand in the shallow near shore zone at the Puget Island site.

SEDIMENT CHARACTER

The sand of the Puget Island Reach was analyzed for grain size distributions by mechanical sieving and settling tube. Settling tube analysis most accurately presents the settling velocity distributions of the grain populations,

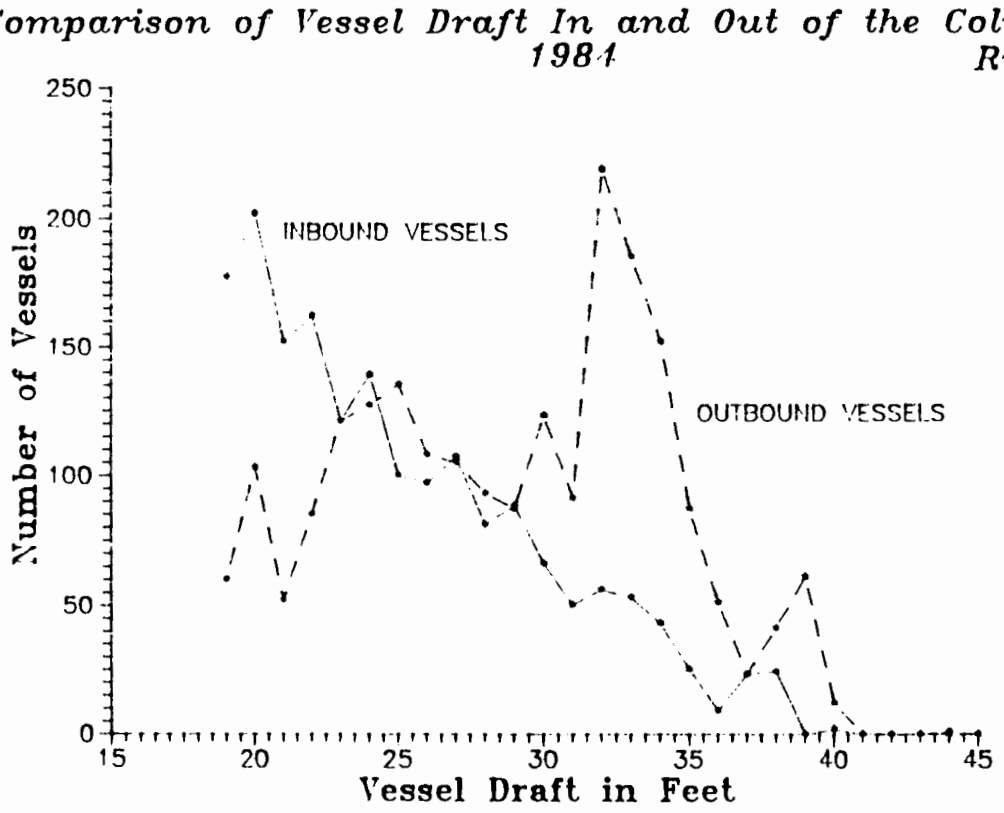


Figure 94. Ship passages in the lower Columbia River.

with size estimation made after calibrating the tube. Calibration results for Columbia River sands of the Puget Island region appear in Figure 95 (calibration curves). In the Puget Island Reach of the Lower Columbia the sediment particles are primarily fine and medium sand (0.25 - 0.50 mm), angular and with an approximate density of 2.60 g/cm^3.

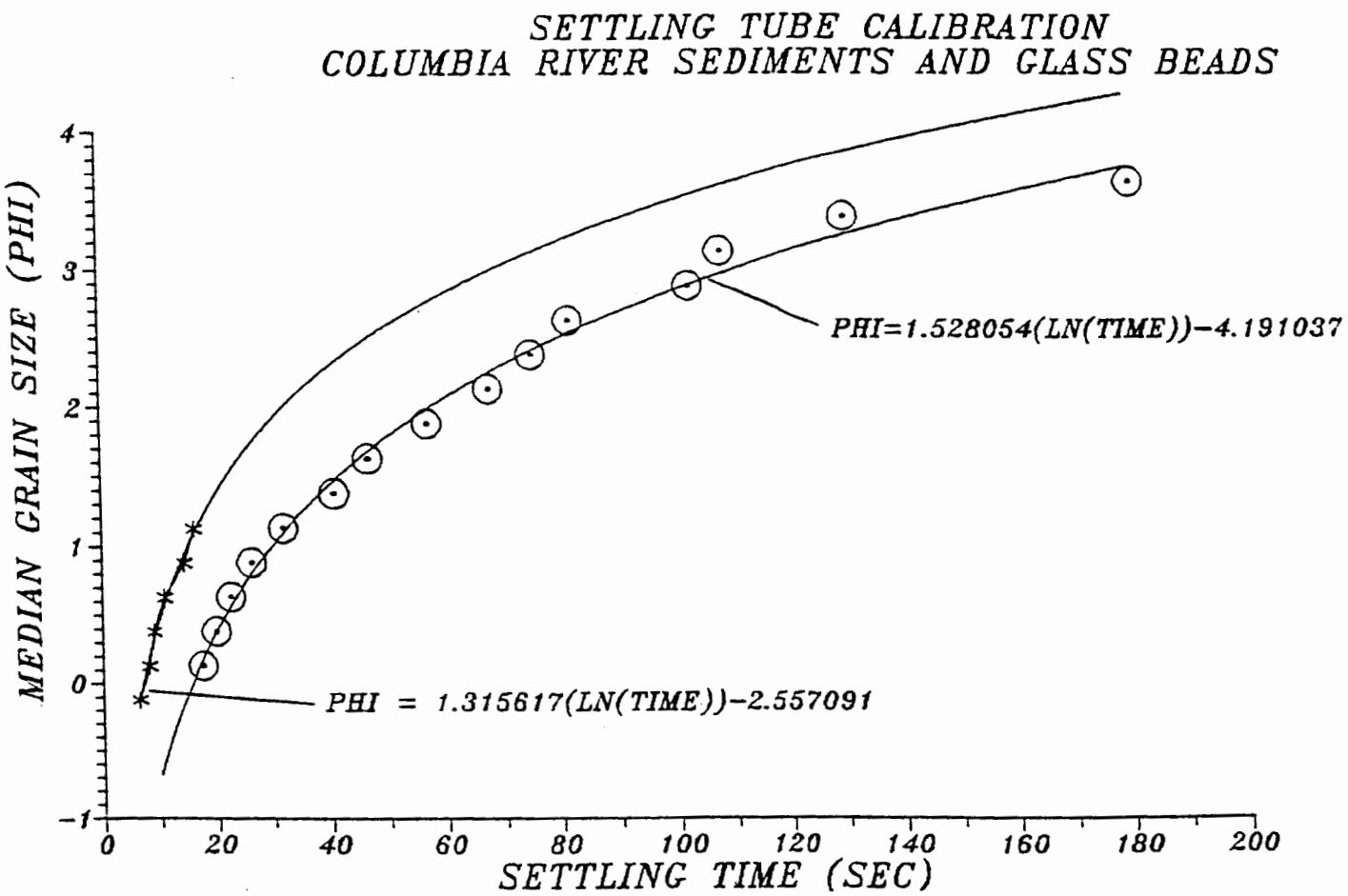


Figure 95. Calibration curves, Puget Island sand.

Sediment Density

The density of common sands is presented in Table XXVIII (USACE, 1984, table 4-2). Table XXIX lists the dry and wet densities and porosities of sand populations along on the Puget Island site (RK 62) and the Gull Island site (RK 88). Knowledge of the density of the shore sands is necessary when a model is constructed to extrapolate volumes of sand moved along the beach. The value of 1,400 kg/m^3 will be used as the representative bulk density for Puget Island sand.

Sediment Size Distribution

The Lower Columbia River sediment is angular plagioclase rich fine to medium sized sand (Figure 96 and Appendix E). The small grain size and relatively low density of the Columbia sand examined indicates that this sediment is easily moved, as based on Shields, Yalin's, or Hjulstrom's sediment motion threshold curves (Shields, 1936; Yalin, 1972; Sundborg and Norrman, 1968; respectively). Sand samples from beach scarp faces eroding into original disposal sites were used to represent the sand making up the shore upon which all physical processes will subsequently interact.

The graphical statistics of sand at the Puget Island site (Folk and Ward, 1957) are presented in Table XXX.

TABLE XXVIII

SEDIMENT DENSITIES

Specific Gravity (dimensionless)

Quartz	2.65
Calcite	2.72
Heavy Minerals	>2.87 (commonly 2.87-3.33)

Sand	Unit Weight kg/m^3 Dry	Saturated
Uniform sand		
loose	1442	1890
dense	1746	2082
Mixed sand		
loose	1586	1986
dense	1858	2163
Clay		
stiff glacial	-	2066
soft, very organic	-	1426

(from Terzaghi and Peck, 1967: in USACE, 1984)

TABLE XXIX

PUGET ISLAND SAND CHARACTERISTICS

Examined for grain density, bulk densities, and porosity

Sand	Dry loose unit weight, kg/m^3	Average Sp. Gravity
PUGET ISLAND		
Channel Dredge porosity = 0.46	1390	2.60
Beach Face porosity = 0.46	1410	2.59
Dune Crest (eolian) porosity = 0.44	1450	2.57
Dune Trough (") porosity = 0.45	1400	2.53
GULL ISLAND		
Active beach face porosity = 0.48	1360	2.64
porosity = 0.42	1380	2.39
MEAN OF SAMPLES (excluding dune sand)		
mean porosity = 0.46	1385	2.56

Sieved Versus Settling Tube Grain Size Analysis

Calibration of the settling tube was compared to the sieve analyses. There is a difference between the two types of analyses, with the settling tube giving a finer distribution than the sieved distribution. The settling tube also suggested a more normal distribution with a slightly positive skew (Φ), not distinguishing a slightly bimodal character of the sediment population which was

TABLE XXX

GRAPHICAL STATISTICS OF COLUMBIA RIVER SANDS

Price, Puget, and Gull Islands, 1987-88.
(All numbers are in phi)

Sample	mean	median	Standard dev.	skew.	kurt.
Scarp face	1.69	1.73	0.44	-0.08	0.88
Beach face	1.87	1.88	0.36	-0.03	0.95
Beach Berm face	1.73	1.76	0.51	-0.06	1.42
Eolian Dune Crest	0.53	0.35	0.69	0.26	0.59
Trough	1.89	1.88	0.44	0.02	1.01

observed in sieve analysis. The interpolated grain size distribution from sieve analysis was compared to a whole sample settling tube size distribution for the two samples and is presented in Figure 96 (grain size curves A-D). Table XXXI presents the graphical statistics for each of these populations.

The distribution of sample grain settling velocities was accurately obtained from the settling tube system. Grains trapped with the bedload sampler (of the shallow water trap arrays) showed higher settling velocities than the sand moved in suspension, as presented in Table XXVI giving data for the passage of the ship "Magnolia". Figure 97 presents a cumulative percent graph of the settling velocities of a representative beach sample.

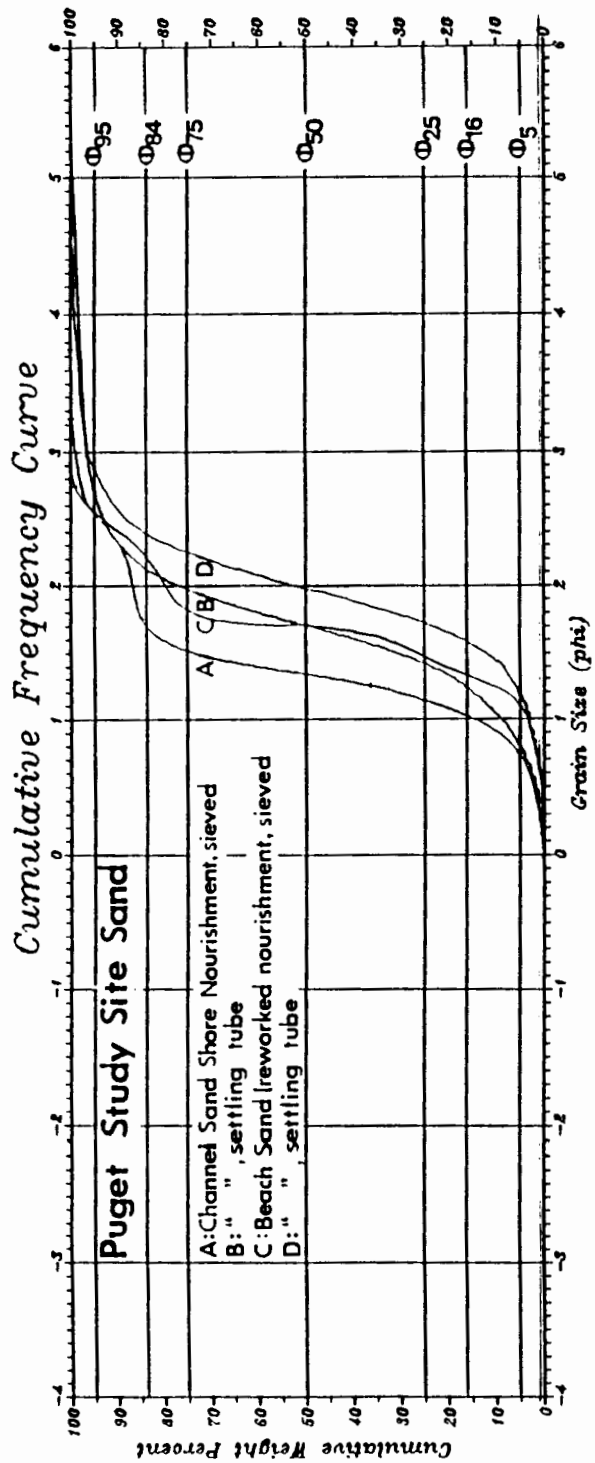


Figure 96. Sediment size distribution curves. For study site sands, using both sieving and settling tube analysis.

TABLE XXXI

GRAIN SIZE STATISTICS

	SAMPLES			
	A	B	C	D
Mean	1.36	1.69	1.75	1.99
Std. Dev.	0.48	0.52	0.46	0.46
Sorting	well	moderate	well	well
Skewness	0.183	0.005	0.180	0.063
	positive	normal	positive	normal
Kurtosis	1.725	1.390	1.685	1.250
peakedness	leptokurtic	leptokurtic	very lepto.	lepto.

Petrography

All sediment samples examined for petrography were derived from dominantly volcanic terrain. This is characteristic for drainage basins west of the Cascades in the Pacific northwest. Samples also include mineral and rock fragments with a crystalline provenance terrain, such as the eastern drainage of the Columbia River. Such crystalline grains include: monocrystalline quartz, schistose rock fragments, potassium feldspar, muscovite, biotite (also found in Cascade dacites and andesites), garnet, spinel, and monazite. These crystalline grains are rare, not occurring with the abundance of the volcanic plagioclase and rock fragments likely derived from the Cascades. Figure 98 presents pie charts illustrating the abundance of primary rock fragments, minerals, and heavy minerals in the lower Columbia River sands.

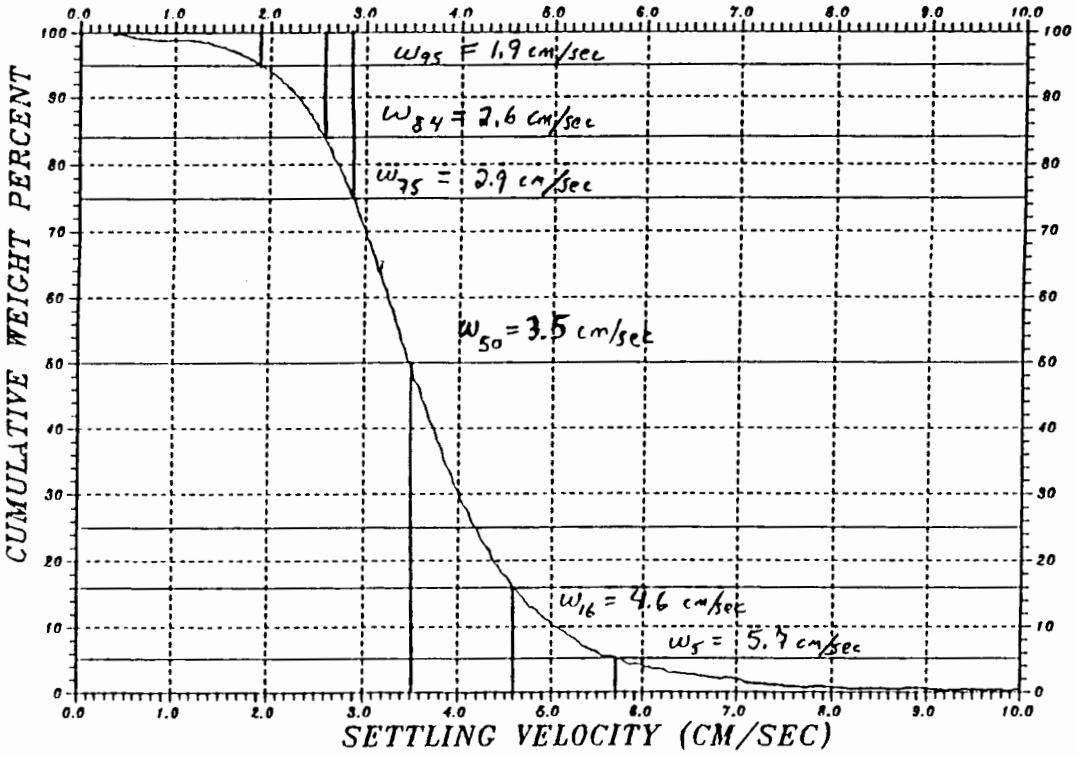


Figure 97. Settling velocities, Puget Island sand. Beach face sample, June 1988.

Grain mounts made of several size fractions were used to determine any relationship between petrography and grain size in the sand population. Two distinct mineral groups were examined, plagioclase and opaque (heavy) minerals. The general hypothesis is that no variation in the percentage of plagioclase with grain size would exist because the characteristically ubiquitous distribution of plagioclase in sediments derived from a volcanic source terrain. Heavy mineral percentages average 10% of the total number of grains and are generally found to increase with finer size fractions as found in other estuarine and

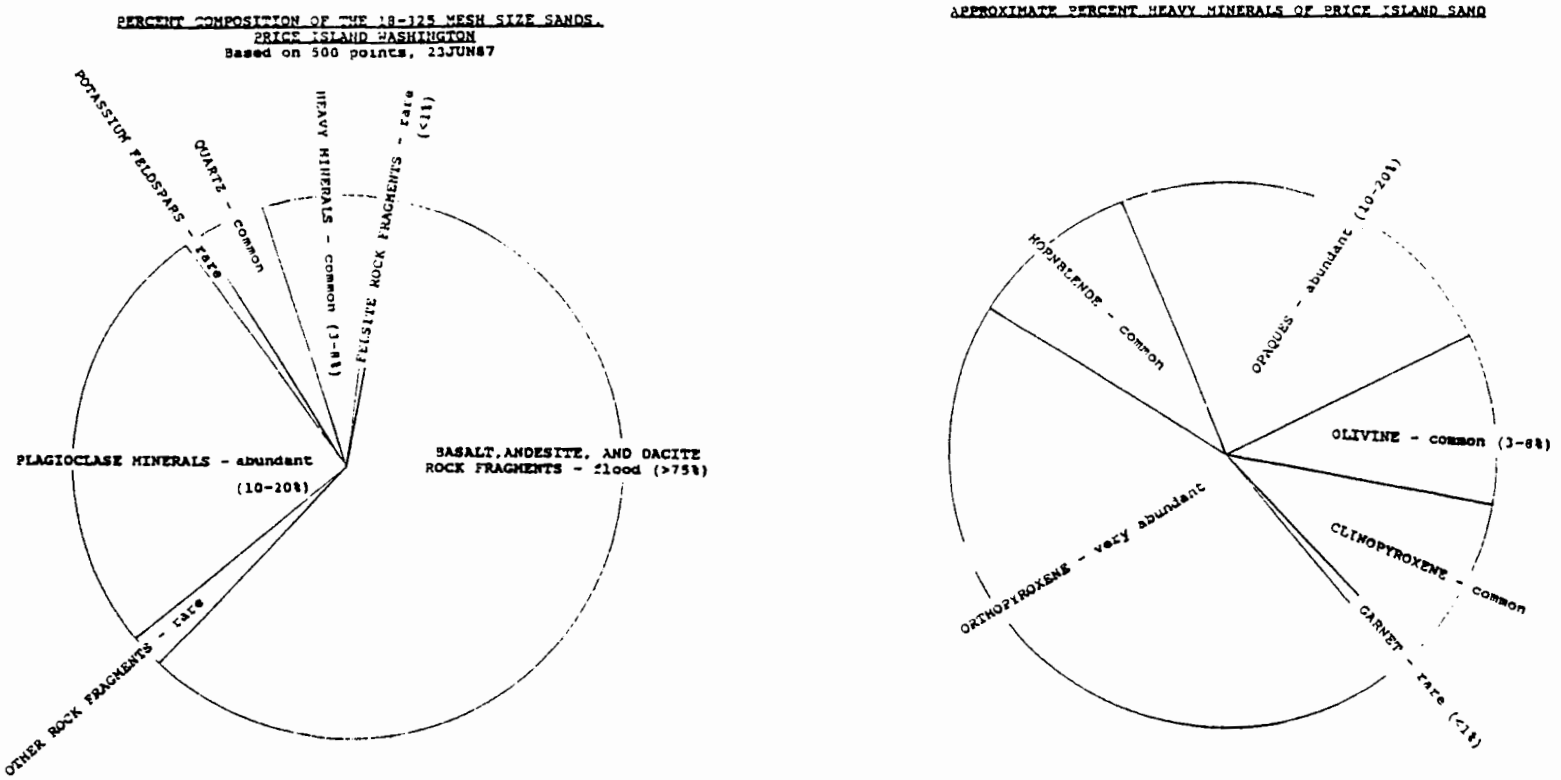


Figure 98. Petrography of lower Columbia sand. Price Island, Washington.

coastal sands (Peterson and others, 1985). Table XXXII presents a simple linear regression and student's t test of significance of the plagioclase content in five size fractions of a one Puget Island site sand. Table XXXIII presents an identical analysis of the opaque content.

The student's t test at the 10% level for the plagioclase-size correlation revealed that the correlation was not significantly different from zero and there is no significant correlation. The same test on the opaque-size correlation revealed a significant difference from zero to the 2.5% level, there is a correlation between increasing opaque percentages with decreasing size fractions.

Figure 99 illustrates the relationship between the percent composition of some of the major minerals and rock fragments found in different grain size ranges. A variety of distinct sedimentary features observed were enhanced by the assemblage of minerals and rock fragments found in the lower Columbia River sand. Hydraulic and aeolian actions segregate the rock and mineral assemblage to form structures that can be preserved in the shore/beach stratigraphy, offering clues in deducing the dominant processes of a sedimentary environment.

TABLE XXXII

LINEAR REGRESSION: PLAGIOCLASE AND GRAIN SIZE

Linear regression and student t test of the percentage of plagioclase in varying size fractions of a Puget Island sample of modern Columbia River channel sand.

n	x_n (phi)	y_n (%)	x^2	xy	y^2
1	-0.50	31.58	0.25	-15.79	997.30
2	0.88	27.33	0.77	24.05	746.93
3	1.88	26.33	3.53	49.50	693.27
4	2.88	32.00	8.29	92.16	1024.00
5	3.88	19.33	15.05	75.00	373.65
$\Sigma^n_{i=1}$ = 9.02		136.57	27.89	224.92	3835.15

$_0$ = 30.64 β_1 = -1.846 y = 30.64-1.846 x
S = 65.30 Γ = 1-(SSE/SST) SST = $\Sigma y^2-(\Sigma y)^2/n$ = 104.88
= correlation(r) = 0.38
1.638 for 10% level
calculated t = $(\Gamma(n-2)^{0.5})/(1-\Gamma^2)^{0.5}$ = 0.711

thus correlation is not significantly different than zero.

TABLE XXXIII

LINEAR REGRESSION: OPAQUE MINERALS AND GRAIN SIZE

Linear regression and student t test of the percentage of opaque minerals in varying size fractions of a Puget Island sample of modern Columbia River channel sand.

n	x_n (phi)	y_n (%)	x^2	xy	y^2
1	-0.50	13.16	0.25	- 6.58	173.18
2	0.88	16.67	0.77	14.67	277.89
3	1.88	41.67	3.53	78.34	1736.39
4	2.88	29.67	8.29	85.45	880.31
5	3.88	59.00	15.05	228.92	3481.00
$\Sigma^{n}_{i=1}$ = 9.02		160.17	27.89	400.80	6528.77

β_0 = 142.83 β_1 = 9.61 y =142.83 + 9.61 x
SSE = 114.22 Γ = 1-(SSE/SST) SST = $\Sigma y^2-(\Sigma y)^2/n$ = 1417.89
Γ = correlation(r)= 0.92
t = 1.638 for 10% level, 2.353 for 5%, 3.182 for 2.5%
calculated t = $(\Gamma(n-2)^{0.5})/(1-\Gamma^2)^{0.5}$ = 4.06

thus correlation is significantly different than zero.

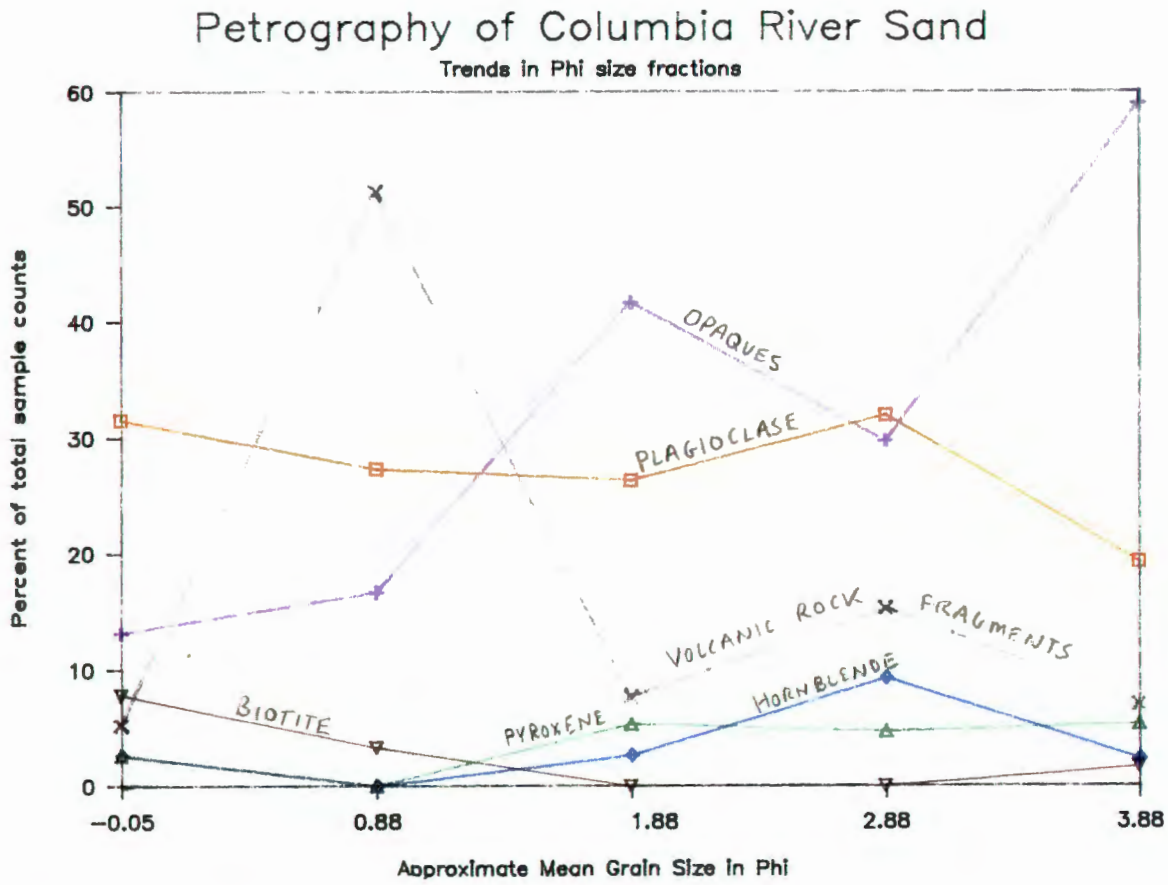


Figure 99. Relationship between grain size and petrography in lower Columbia sand. Phi sizes represent intermediate grain axis length.

CONCLUSION

The shore slopes of the lower Columbia River reflect a variety of physical processes. Ship waves play an important role in the transport of sediments in the shallow water regions of shore slopes in proximity to the navigation channel. Theoretical derivations and data collected in the field suggest that ship wave generated currents instigate sediment movement.

SHORE EROSION

The results of examining historic aerial photographs and map records showed that Price Island and Puget Island have traditionally experienced erosion. Gull Island has experienced a accretion with time due to dredge disposals.

Profiling of three study sites shows a considerable variation in the rates of erosion along beach nourishments of the Puget Island Region of the lower Columbia River.

Hypothetically, the most rapid loss of sand is expected immediately after nourishment since that is the period in which the artificial deposit is most unstable. But this could not be substantiated by this study and can be misleading in the case of shore notches which can exhibit high erosion rates well after emplacement of the nourishment. Profiling revealed that the shore notch

exhibits a much higher rate of erosion than any other locality along a site.

Two sites, Price Island and Puget Island both displayed local zones of very high erosion as well as apparently stable beach slopes. The Gull site showed some erosion after nourishment, but in general remained a stable site. The total estimates of sand lost in the shallow water nearshore zone are presented in Table XXXIV.

TABLE XXXIV

STUDY SITE EROSION

Site	July 1987 - July 1988 Volume Lost (m^3)
Price Island, WA	27,729
Puget Island, WA	26,197
Gull Island, OR	4,266

GEOMORPHIC OBSERVATION AND DEVELOPMENT

A variety of distinct and characteristic geomorphic forms of an active sandy shoreline have been described. The shore forms and sedimentary structures presented in this study show that sand is reworked by several physical processes that include; wind, wind generated water waves, tidal fluctuations, and ship waves.

Beach scarps are strong evidence of continued wave action and unstable beach slopes. Beach scarps suggest

active sediment contribution to the beach face. On a smooth beach face at the northwest end of Puget Island, Washington, sediment transport analyses showed a net offshore flux. Wave generated features were the most common structures observed on the shore surface and trench stratigraphy. The lack of some structures, such as ripples not being preserved in beach stratigraphy is the result of ship wave actions.

The shore notch is composed of two components: an erosive scarp in the upper beach and an accreting lobe on the lower beach face. The shore notch is attributed to ship wave actions. The shore notch was shown to be a zone of accelerated erosion in which sand is transferred from the upper beach nourishment to the beach face. Sediment character across the shore notch shows a distinct grain coarsening toward the notch.

SEDIMENT TRANSPORT

Observations of sedimentary structures at the study sites and sediment trap data from the Puget Island site show that wind instigates sediment entrainment in both the subaerial and shallow subaqueous environments. This sediment entrainment appears to account only for a small portion of total sediment transport. Wind and water wave actions are responsible for the retreat of beach scarps. Wind generated water waves create ripple bedforms in

shallow water, but apparently cause very little net sand transport. During peak freshwater currents, sediments begin to move in shallow water depths of 50 cm and more, with increasing flux in deeper water. Sediment transport by ebb currents is not important in water depths less than two meters along the Puget Island site.

SHIP WAVES

Ship waves are a set of waves that vary greatly in size and period. This study has used established theory regarding the drawdown wave (long period) and the maximum secondary wave (short period) to show that both types of waves are capable of moving sand in shallow water regions. The direction in which sand particles move on the beach surface can also be predicted by calculating the near-bed shear velocities vectors.

Local land owners along the river remarked upon the impact of ship generated waves on the shore. Resident observations have been noted in reports on analogous systems in North America and Europe. Ship wave observations made along the lower Columbia River are similar to those in other works (Ofuya, 1970; Sorensen, 1973; Sorensen and Weggel, 1984; Span and others, 1981; Balanin and others, 1981).

A significant difference in draft between ships moving downstream and those moving upstream could not be

established. Downstream passage of deep draft ships should instigate greater sediment transport than upstream passage, because of the increased displacement of outbound ships. Data suggests no significant difference between downstream ship velocities versus upstream velocities. Holding velocity constant the most critical variables become ship draft and channel cross-sectional area. Because most deep draft ships time their outbound passages to coincide with high water elevations, the increased channel cross-sectional area will dampen the effect of increased ship draft, thus it is possible that the increased draft of outbound ships may would not cause a substantial increase in the size of waves generated by the same ship on its inbound passage. But geomorphic observations show the net longshore sediment transport is downstream, suggesting that outbound ships have a greater impact than inbound ships. The other explanation of the downstream longshore sediment transport is that ebb currents have a greater impact than observed in this study, such as during anomalous storm events, high flow releases, and/or spring tides.

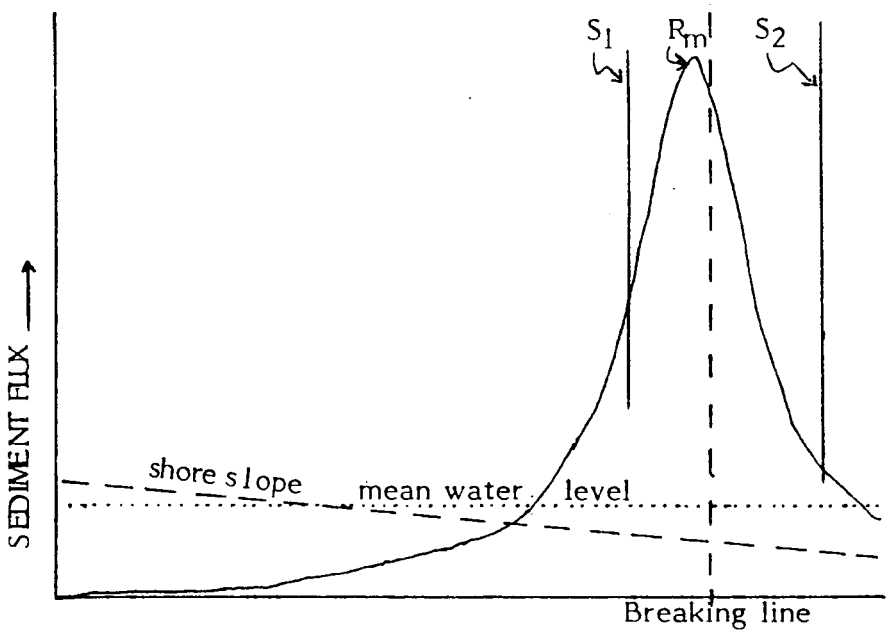
Sediment Transport by Ship Induced Water Motions

Ship waves deliver energy to the shore in the form of several distinct water motions. These hydraulics are responsible for a part of the sediment transport along the shore slope. The magnitude of each wave set dictates the

manner in which sediment transport occurs. The problem of examining ship wave processes in a channel such as the lower Columbia River involves a complicated set of processes. A simple model was delineated and applied to sediment transport on a smooth beach face at the Puget Island study site. The illustrates the movement of sand and resulting changes in a beach form. Over time the upper beach undergoes degradation, the lower beach experiences aggradation, and net longshore drift results in accretionary lobes of sand, as observed at the north end of the Puget site. This model (3,600 ship passages) estimated an offshore sediment flux between 1,028 m^3 to 6,364 m^3 for the Puget Island site, 4 to 24 percent of the surveyed sediment volume that eroded. Using the sediment transport caused by the waves of naval ships, an upper limit of offshore sediment flux was derived using the same method to be 73,478 m^3, 2.8 times the 26,197 m^3 that eroded from the site.

The model was based on measured sediment flux at points on the beach face. These point samples give a limited distribution of flux through the surf zone that is unlikely to record the peak flux actually occurring. Because sediment flux through the surf zone is interpreted to have an exponential distribution perpendicular to the shoreline, the change in flux over a relatively small distance near the line of wave breaking can be dramatic.

Thus the maximum measured flux is unlikely to represent the maximum point flux, as illustrated in Figure 100. The maximum measured flux must be less than or equal to the true maximum flux, as seen in Figure 100. It is concluded that the maximum error, up to several orders of magnitude, is introduced in the field sampling method of measuring flux only at single points.



S_1 = maximum measured sediment flux
S_2 = minimum measured sediment flux
R_m = real maximum sediment flux

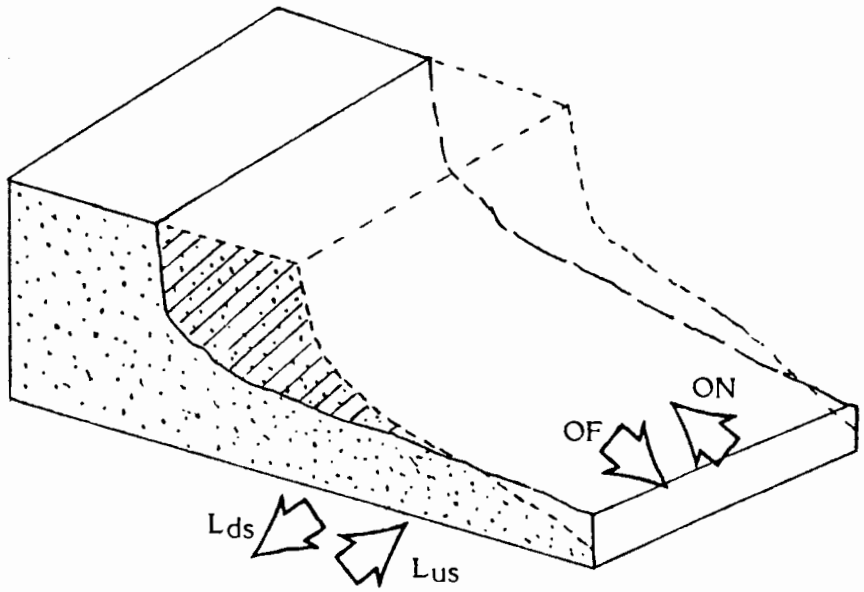
S_1 .LE. R_m

Figure 100. Surf zone sediment flux distribution. Interpretation of true flux distribution through the surf zone and measured points.

MASS BALANCE OF MEASURED VALUES AND SOURCES FOR ERROR

The difference between sediment moving into and out of a beach cell provides a measure of accuracy of sediment transport measurements and extrapolations, based on the conservation of mass. A mass balance, as schematically presented in Figure 101, was done using measures of sediment transport on the shore slope, in the shallow water intertidal region. Particular factors introducing error in the mass balance equation and used to resolve mass discrepancy of sediment transported along the shore. I suggest that the largest source of error is the maximum value of measured sediment offshore flux by trap used to represent maximum point flux. It has been presented that offshore flux dramatically increases through the surf zone and decreases rapidly beyond the breaking line in this study and other investigations (Kraus, 1987; King, 1972; Hallimeier, 1982).

Because of peaked distribution of sediment flux in the surf zone, measuring the point of maximum flux is nearly impossible without a continuous sampling regime through the surf zone. Accurate wave predictions can enable the best positioning of limited number of samplers. Using the point sampling regime established in this study, it was unlikely to sample the true peak flux. The value of flux used in the sediment transport extrapolations



= Original sand disposal (shore nourishment)

= Sand volume eroded after time t

= Sediment transport

OF = offshore transport; ship waves, wind waves, gravity

ON = onshore transport; ship waves, wind waves

L_{ds} = longshore transport; ship waves, wind waves, ebb currents

L_{us} = longshore transport; ship waves, wind waves, flood tide currents

Ideal mass balance: mass into beach cell = mass out of beach cell

Figure 101. Mass Balance. Schematic illustration of mass balance in near-shore beach cell, such as the Puget Island site.

presented are assumed to underestimate peak flux, probably by several order of magnitudes.

An annual ebb current sediment transport rate along the shore was calculated to be approximately 12 cubic meters.

Using the maximum measured longshore transport measured for the ship passages observed of 18.2 kg/m in the upstream direction and a zone of transport perpendicular to the shoreline of 5 meters, and 1,500 (one way) ship passages per year reveals an annual transport volume of 98 cubic meters. Because ships also move in the opposite direction, there is a transport component that would negate part or all the extrapolated value of 98 cubic meters per year. Based on theoretical derivation of ship waves (Havelock, 1931; Saunders, 1975; Sorensen and Weggel, 1984; Johnson, 1968; Constantine, 1961; and others) and field observations (Ofuya, 1970; Brebner and others, 1966; Sorensen, 1973) identical ships with the same displacement moving at increasing velocities will cause an increase in wave height proportional to ship velocity squared; for ships moving at the same velocity but with increased displacement, the relationship to wave height is less clear, but wave height does increase. Barrass (1979) presented ship squat (ship draft relative to the bed, not the water surface) to be a linear function of the blockage factor; the blockage factor is the ship's cross sectional

area relative to the channel cross sectional area. It is assumed from the observations made during this study and the Columbia River Pilots, there is no consistent difference in the velocity of upstream and downstream ships in the lower Columbia River navigation channel. But it is clear that a dramatic difference exists between the displacements of ships moving upstream and downstream in the lower Columbia (USACE, Waterborne Commerce, 1970-1986; Columbia River Pilots, 1987-1988). The lower Columbia navigation system exports 4 to 6 times the tonnage that is imported (main exports are bulk commodities: grain and timber). It can be deducted from higher export tonnages and assuming equivalent ship velocities, that will be a net downstream longshore sediment flux. The records of this study did not substantiate that outbound moving ships move more sediment along the shore than inbound moving ships. But a export tonnage of 4 times the import tonnage and a proportional increase in the impact of ship waves, the resulting downstream longshore sediment flux would be about 74 m^3/year.

Equation (23) presents the mass balance solution of sediment into and out of the Puget Island site:

$$Q_t = L_{ds} - L_{us} + L_{de} - L_{uf} + L_w - On_s + Of_s - On_w + Of_w \qquad (23)$$

Q_t = Total sediment removed from site

L_{ds} = Downstream longshore transport by ship waves

L_{us} = Upstream longshore transport by ship waves

L_{de} = Downstream longshore transport by ebb current

L_{uf} = Upstream longshore transport by flood current

L_w = Longshore transport by wind generated water waves (net upstream)

On_s = On-shore transport by ship waves

Of_s = Off-shore transport by ship waves

On_w = On-shore transport by wind generated water waves

Of_w = Off=shore transport by wind generated water waves

The values of each of factors (cubic meters):

Q_t = 26,197

L_{ds} = 98

L_{us} = 24

L_{de} = 12

L_{uf} = 0

L_w = 1

On_s = 23,397

Of_s = 29,761

On_w = 0

Of_w = 0

($On_w > Of_w$)

Merchant ship wave derivation (cubic meters of sand):

26,197 = 98 - 24 + 12 - 0 + 1 - 23,397 + 29,761 - 0 + 0

26,197 = -6,451

Naval ship wave derivation (cubic meters of sand):

26,197 = 98 - 24 + 12 - 0 + 1 - 119,764 + 46,286 - 0 + 0

26,197 = -73,391

Error = -47,194

No sediment mass was ever observed to be moved off- or on-shore by wind waves (on_w off_w), but a conservative estimate was calculated using the same proportions found between longshore transport and on- offshore transport by ship waves.

The discrepancy between the total volume eroded from the Puget Site beach and the amount moved from the site by the dominant physical factors can be only postulated by considering the most reasonable sources of error. Because offshore transport by ship waves accounted for the vast majority of observed sediment transport, it is concluded that under mean weather and river flow conditions such as those observed, it is ship waves that instigate the vast majority of sediment transport. This conclusion is based on the fact that even though ship waves occur as an anomalous event, the energy to they deliver to the shore usually exceeds the threshold conditions for transport of the bed material whereas other processes observed such as wind and ebb currents do not sufficiently surpass threshold conditions to cause appreciable sand transport. It is the instantaneous energy (in the form of a shear force) that will determine the importance of a process in sediment

transport. Even if the cumulative energy delivered to the shore by wind generated water waves or tidal currents exceeded the cumulative ship wave energy, if the instantaneous energy supplied by these processes cannot surpass the threshold conditions of the sediment, the processes are secondary to ship waves. The error in the mass balance is probably not an unaccounted process, but rather an error in representative measure of maximum sediment transport by ship waves.

The other plausible source of error comes from the impact of anomalous storm, spring tide, or high flow release events. A storm generating waves similar size in to ship generated waves could in one day (twenty-four hours) do as much (more given concentration of energy in small period of time) sediment transport as about 480 ships (a two month period). Further observations during times of high river discharge and storm events are needed to evaluate the importance of these events in near-shore shallow water sediment transport.

SEDIMENT CHARACTER

The sediments of the Columbia River channel in the Puget Island study region are primarily composed of a well sorted fine to medium subrounded to angular volcaniclastic sand. Some of the muscovite population seen in the lower Columbia sands may be recycled mica of the regional

sedimentary formations such as the Astoria, not necessarily the exclusive product of the Columbia River's present-day eastern plutonic drainage terrains.

Settling tube analysis suggests that the sand populations behave unimodally in their settling velocities. The anomalous grains in the population exhibit distinct preference on the beach, such as pumice swash at high water lines, heavy mineral banding along high water berms. Thus certain sediments can act as excellent markers on the beach face for the interpretation of different hydraulic regimes.

FUTURE WORK

Much of the work done in this study has brought to bear questions concerning the lower Columbia River's shore response to the primary physical processes of tidal currents, wind, and ship waves.

Suggestions concerning the nearshore sediment trap array and elaborating on a sediment flux model include:

Sample at more locations in a line perpendicular to the shoreline to define a function more descriptive of sediment transport in a unit cell of beach.

Account for wave refraction, changing wave incidence along a unit beach or use a step function model that splits up site into cells based on changes in wave characteristics.

Examine transport in deeper water, the channel slopes in depths between 2 to 8 meters.

Better estimate ship distance from shoreline.

REFERENCES

Abbe, T., 1988a, Report on the Geology and Geomorphology of Price Island, WA, In: US Army Corps of Engineers Portland District, Price Island Erosion Control Study, Reconnaissance Report, September 1988, Portland, OR.

Abbe, T., 1988b, Ship wave theory and shallow water sediment transport in the Lower Columbia River, U.S.A. [abs.], Pacific Northwest American Geophysical Union 35th Annual Meeting Abstracts, Victoria, Canada.

Abbe, T., 1989, Wave energy and resulting sand transport on the shore slopes of the Lower Columbia River, WA and OR, In: Coastal Zone 89 Proceedings, paper 226, American Society of Civil Engineers, Charleston, SC.

Abbe, T., Johnson, A. J., Thoms, R. E., and Eriksen, K., 1988, Nearshore sand transport by wave energy on the shore slopes of the Columbia River, the Puget Island Reach, Oregon and Washington [abs.], Oregon Academy of Sciences 1988, Portland State University, Portland, OR.

Abbe, T., and Phan, T., 1987, A preliminary report on the design and implementation of a sediment transport study on the shore slopes of the Columbia River in the Puget Island Reach, Oregon and Washington [abs.], Pacific Northwest Region of the American Geophysical Union 34th Annual Meeting Abstracts, Olympia, WA.

Abou-Seida, M.M., 1965, Bedload function due to wave action, Hydraulic Engineering Laboratory, Wave Research Projects, University of California, Institute of Engineering Research Technical Report HEL-2-11, Berkeley, CA.

Airy, G.B.,1845, On tides and waves: Encyclopedia Metropolitana, v.5, pp. 241-396.

Allen, J.E., 1987, Cataclysms on the Columbia, Timber Press, Portland, OR, 211 p.

Allen, P.A., 1981, Wave-generated structures in the Devonian lacustrine sediments of south-east Shetland and ancient wave conditions, Sedimentology, v.28, pp. 369-379.

Anderson, L., 1985, The development of modern Columbia River navigation, Bulletin of the Permanent International Association of Navigation Congresses, no.51, pp. 37-43.

Ando, M. and Balazas, E.I., 1979, Geodetic evidence for a seismic subduction of the Juan de Fuca plate, Journal of Geophysical Research, v.84, pp. 3023-3028.

Araya-Vergara, J.F., 1986, Toward a classification of beach profiles, Journal of Coastal Research, v.2, pp. 159-165.

Bagnold, R.A., 1946, Motion of waves in shallow water; interactions between waves and sand bottom, Proceedings of the Royal Society,(London), series A, 187:1-15.

Bagnold, R.A., 1963, Beach and Nearshore Processes, IN: Thorne, C.R., MacArthur, R.C., and Bradley, J.B.[eds.], 1988, The Physics of Sediment Transport by Wind and Water, American Society of Civil Engineers, NY, NY, pp. 188-230: Article originally published in: Hill, M.N.[ed.], 1963, The earth beneath the Sea, vol. 3 of "The Sea--Ideas and Observations on Progress in the Study of the Seas, Wiley-Interscience, London, pp.507-553.

Bagnold, R.A., 1966, An approach to the sediment transport problem from general physics, U.S. Geological Professional Paper 422-I, Washington, D.C., 37 p.

Bagnold, R.A., 1983, The nature and correlation of random distributions, Proceedings of the Royal Society of London, Series A, v.388, pp. 273-291.

Bagnold, R.A., and Barndorff-Nielsen, O. E., 1980, The pattern of natural size distributions, Sedimentology, v.27, pp. 199-207.

Balanin, V., Bykov, L., Zernov, D., Metelytsina, G., and Natalchishin, G., 1981, Means of protecting waterway slopes and beds from streams and waves, including ship effect, Inland & Maritime Waterways & Ports, Section I Inland Waterways & Ports, vol.1, 25th International Navigation Congress, Edinburgh, pp.167-182.

Barrass, C.B., 1979, A unified approach to "squat" calculations for ships, Permanent International Association of Navigation Congresses, v.1, pp. 3-10.

Bascom, W.N., 1951, The relationship between sand size and beach face slope, Transactions of the American Geophysical Union, v.32, pp.866-874.

Beeman, O., 1985a, Studies to control shoaling of the navigation channel, Lower Columbia River, unpublished report to Portland District Operations Branch of U.S. Army Corps of Engineers, Portland, OR.

Beeman, O., 1985b, Channel optimization - the Columbia River deep draft navigation project, Permanent International Association of Navigation Congresses Bulletin, no.51, pp.44-51.

Bekendam, A.J., Blok, P.M, de Boer, W., Bos, M., Brolsma, J.U., van der Burg, J., Deelen, C., van Doorn, J.T.M., Filarski, R., Havinga, H., Heinen, H.G., Koeman, J.W., Leemans, J.A.A.M., Rem, A., Schulffel, H., van Schuylenburg, M., Steentjes, J.B.W., Verney, H.J., Veldhuyzen, W., de Vries, W., Wels, H., van der Weijde, R., [Brolsma, J.U.(Coordinator)], 1988, Six-Barge Pushtow Trials, Bulletin of the Permanent International Association of Navigation Congresses, no.62, pp. 21-84.

Bidde, D.D., 1968, Ship waves in shoaling water, Hydraulic Engineering Laboratory College of Engineering, University of California, Berkeley, CA, 32 pp.

Birkemeier, W.A., 1988, The interactive survey reduction program (ISRP), version 1.25, Feb. 1986, U.S. Army Waterways Experiment Station, Vicksburg, MI.

Blatt, H., Middleton, G., and Murray, R., 1980, Origin of Sedimentary Rocks, 2nd Ed., Prentice-Hall, Inc., Englewood Cliffs, NJ.

Borgeld, J.C. and others, 1978, A geological investigation of sedimentary environments at sites E, G, and H, near the mouth of the Columbia River, University of Washington Department of Oceanography, Seattle, WA; In: Gordon, M. (chairs), 1980, A literature survey of the Columbia River Estuary, v.II, Annotated Bibliography, Columbia River Estuary Data Development Program, Pacific Northwest River Basins Commission, Vancouver, WA.

Brebner, A., Helwig, P.C., and Carruthers, J., 1966, Waves produced by ocean-going vessels: a laboratory and field study, IN: 10th conference on Coastal Engineering, chapter 28, Tokyo, Japan, pp. 455-465.

Brenninkmeyer, B.M., 1975, Frequency of sand movement in surf zone; Proc. 14th conf. on coast. eng., pp.812-827.

Chelton, D.B. and Davies, R.E., 1982, Monthly mean sea-level variability along the west coast of North America, Journal of Physical Oceanography, v.12, pp.757-784.

Clemens, K.E. and Komar, P.D., 1988, Oregon Beach-sand compositions produced by the mixing of sediments under a transgressing sea, Journal of Sedimentary Petrology, v.58, no.3, pp. 519-529.

CRPA (Columbia River Pilots Association), 1987-1988, Data on Vessel Drafts (unpubl.), Columbia River Pilots Association, Portland, OR.

Constantine, T., 1960, On the movement of ships in restricted waterways, Journal of Fluid Mechanics, v.9, pp. 247-257.

Constantine, T., 1961, The behavior of ships moving in restricted waterways, Institution of Civil Engineers, Proceedings, v.19, London, pp. 549-562.

Cook, D.O. and Gorsline, D.S., 1972, Field observations of sand transport by shoaling waves, Marine Geology, v.13, pp. 31-55.

Crowson, R.A., Birkemeier, W.A., Klein, H.M., and Miller, H.C., 1988, Superduck nearshore processes experiment: summary of studies, CERC Field Research Facility, CERC (Coastal Engineering Research Center), U.S. Army Waterways Experiment Station, Technical Report CERC-88-12, Vicksburg, MI.

CRWMG (Columbia River Water Management Group, 1988, Columbia River Water Management Report for Water Year 1987, Mark Maher [Chairman], Bonneville Power Administration, Portland, OR.

Curray, J.R., 1965, Late Quaternary history, continental shelves of the United States, IN: The Quaternary of the United States, Wright, H.E. and Frey, D.G., Princeton University Press, pp.723-735.

Das, M.M., 1969, Relative effects of waves generated by large ships and small boats in restricted waterways, Technical Report HEL 12-9, Hydraulic Engineering laboratory, University of California, 112 pp.

Davies, A.G., 1985, Field Observations of the Threshold of Sediment Motion by Wave Action, Sedimentology, v.32,p.685-704.

DeRaaf, J.F.M., Boersma, J.R., and Van Gelder, A., Wave generated structures and sequences from a shallow marine succession, Lower Carboniferous, County Cork, Ireland, Sedimentology, v.24, no.4, pp. 451-485.

Dyer, K.R., 1986, Coastal and Estuarine Sediment Dynamics, John Wiley and Sons, 342 pp.

Dunne, T. and Leopold, L.B., 1978, Water in Environmental Planning, W. H. Freeman and Co., New York.

Eagleson, P.S. and Dean, R.G., 1966, Small amplitude wave theory, In: Ippen, A.T.(Ed.), Estuary and Coastline Hydrodynamics, McGraw-Hill Book Co., Inc., New York, pp. 1-92.

Einstein, H.A., 1972, A basic description of sediment transport on beaches, IN: Meyer, R.E.(ed.), 1972, Waves on beaches and resulting sediment transport, Academic Press, New York.

ENR (Engineering News-Record), 1987, McGraw-Hill, Inc., September 3, p.14.

Eriksen, K.W., 1988, personal communication, research on dredging activities in the Lower Columbia River (unpubl.), MIR (Maintainence Improvement Review, Hydraulics and Hydrology Branch, Portland District, U.S. Army Corps of Engineers.

Eriksen, K.W., 1989, Columbia River - Puget Island Reach Hydraulic and Sedimentation Analysis, U.S. Army Corps of Engineers Portland District, CENPP-EN-HY memorandum for files (unpubl.), 13MAR1989.

Farr, L. and Abbe, T., 1987, Sand Dispersal on a Puget Island Beach Along the Columbia River: An Investigation of Quantitative Methods, final research project for G474, Geomorphic Processes, Prof. L. Palmer, Portland State University Geology, Portland, OR, 23 pp.(unpubl.).

Folk, R.L. and Ward, W.C., 1957, Brazos River Bar: A study in the significance of grain size parameters, Journal of Sedimentary Petrology, v.27, pp.3-27.

Fuehrer, M., Romisch, K., and Engelke, G., 1981, Criteria for dimensioning the bottom and slope protections and for applying the new methods of protecting navigation canals, Inland & Maritime Waterways & Ports, Section II Maritime Ports and Seaways, v.5, 25th International Navigation Congress, Edinburgh, pp. 29-40.

Galvin, C.J., Jr.,1969, Breaker travel and choice of design wave height, Journal of the Waterways and Harbors Division, American Society of Civil Engineers, WW2, v.95, paper 6569.

Galvin, C.J., 1972a, Wave breaking in shallow water, In: Waves on Beaches and Resulting Sediment Transport, Academic Press.

Galvin, C.J., 1972b, A gross longshore transport rate formula, Proceeding of the 13th Coastal Engineering Conference, Vancouver, B.C., Canada, July.

Galvin, C.J., Jr. and Eagleson, P.S., 1965, Experimental study of longshore currents on a plane beach, TM-10, U.S. Army Corps of Engineers, Coastal Engineering Research Center, Washington D.C.

Gomez, B. and Church, M., 1989, An assessment of bed load sediment transport formulae for gravel bed rivers, Water Resources Research, v.25, no.6, pp.1161-1186.

Goncharov, V.N., 1938, Movement of Sediments in a Steady Stream, ONTI, Moscow.

Gordon, M. (chairman), 1980, A literature survey of the Columbia River Estuary, v.II, Annotated Bibliography, Columbia River Estuary Data Development Program, Pacific Northwest River Basins Commission, Vancouver, WA.

Graf, W.H., 1971, Hydraulics of Sediment Transport, McGraw-Hill Book Co., 513 pp.

Guilloton, R.S., 1960, The Waves Generated by a Moving Body, The Royal Institution of Naval Architects, Quarterly Transactions, v.102, no.2, pp. 157-173.

Hails, J. and Carr, A. [Eds.], 1975, Nearshore Sediment Dynamics and Sedimentation, An Interdisciplinary Review, John Wiley and Sons, London.

Hallermeir, R.J., 1982, Bedload and wave thrust computations of alongshore sand transport, Journal of Geophysical Research, v.87, no.C8, pp.5741-5751.

Hartmann, D., 1988, The goodness-of-fit to ideal Gauss and Rosin distributions: a new grain-size parameter - Discussion, Journal of Sedimentary Petrology, v.58, no.5, 913-917.

Hay, D., 1968, Ship waves in navigable waterways, Proceeding of 11th conference on Coastal Engineering, chapter 95, London, England, pp. 1472-1487.

Havelock, T.H., 1931, Ship waves: the calculation of wave profiles, Proceedings of the Royal Society, Section A, pp. 1-13.

Heller, P.L., Tabor, R.W., and Suczek, C.A., 1987, Paleographic evolution of the United States Pacific Northwest during Paleogene time, Canadian Journal of Earth Science, v.24, pp. 1652-1667.

Hertzberg, R., 1954, Wave-wash control on Mississippi River levees, Proceedings of the American Society of Civil Engineers, v.119, pp. 628-638.

Hjulstrom, F., 1939, Transportation of detritus by moving water, IN: Trask, P.D.(Ed.), Recent Marine Sediments A Symposium, The American Association of Petroleum Geologists, Dover Publications, London.

Horikawa, K. and Watanabe, A.,1967, A study on sand movement due to wave action, Coast. Eng. in Japan, 10, 39-57.

Howd, P.A., and Holman, R.A., 1987, A Simple Model of Beach Shore Response to Long Period Waves, Marine Geology, v.78, p.11-22.

Hubbell, D.W., Stevens, H.H., Skinner, J.V., and Beverage, J.P., 1986, Characteristics and use of Helley-Smith type bedload samplers, U.S. Geological Survey open file report OF86-415W.

Hubbell, D.W., Laenen, J.M. and McKenzie S.W., 1983, Characteristics of Columbia River Sediment Following the Eruption of Mount St. Helens on May 18, 1980, USGS Circular 850-J.

Ingle, J.C.,1966, The movement of beach sand, Elsevier, NY, 221 pp.

Inman, D.L., 1952, Measures for describing the size distribution of sediments, Journal of Sedimentary Petrology, v.22, no.3, pp. 125-145.

Ikeda, S., 1982, Lateral bed loads transport on side slopes, Technical Notes, Journal of the Hydraulics Division, American Society of Civil Engineers, v.108, no. HY11, pp.1369-1373.

Ippen, A.T., ed., 1966, Estuary and Coastline Hydrodynamics, McGraw-Hill Book Company.

Ippen, A.T. and Eagleson, P.S., 1955, A study of sediment sorting by waves shoaling on a plane beach, U.S.Army Corps of Engineers, Beach Erosion Tech. Memo no.63, 83pp.

Jane's, 1987-88, Jane's Fighting Ships 1987-88, Jane's Publishing Company, Ltd., London, UK, pp. 696-808.

Jay, D., 1984, Circulatory Processes in the Columbia River Estuary, Final CREDDP Report (Columbia River Estuary Data Development Program), CREST (Columbia River Estuary Study Taskforce), Astoria, OR, 169 pp.

Johnson, J.W., 1956, Dynamics of Nearshore Sediment Movement, Bulletin of the American Society of Petroleum Geology, 40, no.9, pp. 2211-32.

Johnson, J.W., 1958, Ship waves in navigation channels, IN: 6th Conference on Coastal Engineering, chapter 40, ASCE, pp. 666-690.

Johnson, J.W., 1968, Ship waves in shoaling waters, Proceedings of 11th conference on Coastal Engineering, chapter 96, London, England, pp. 1488-1498.

Katori, S., 1982, Measurement of sediment transport by streamer trap, Report of the 6th Cooperative Field Investigation, Nearshore Environment Research Center, Report no. 16, TR-82-2, pp. 138-141. (in Japanese).

Katori, S., 1983, Measurement of sediment transport by streamer trap, Report of the 7th Cooperative Field Investigation, Nearshore Environment Research Center, Report No. 17, TR-82-1, pp. 110-117. (in Japanese).

Kelley, J.C. and Whetten, J.T., 1969, Quantitative Statistical Analyses of Columbia Sediment Samples, Journal of Sedimentary Petrology, v.39, no.3, pp. 1167-1173.

King, C.A.M., 1972, Beaches and Coasts, Edward Arnold, Ltd., London, (pp. 43-191; pp. 215-381).

Knebel, H.J., Kelley, J.C., and Whetton, J.T., 1968, Clay minerals of the Columbia River: a qualitative, quantitative, and statistical evaluation, Journal of Sedimentary Petrology, v.38, pp. 600-611.

Komar, P.D., 1971, Mechanics of Sand Transport on Beaches, Journal Geophysical Research, v.76, no.3, 716-721.

Komar, P.D., 1975, Nearshore currents: generation by obliquely incident waves and longshore variations in breaker height, In: Hails, J. and Carr, A.[Eds.], 1975, Nearshore Sediment Dynamics and Sedimentation, An Interdisciplinary Review, John Wiley and Sons, London.

Komar, P.D., 1976, Beach processes and sedimentation, Prentice-Hall, Inc., Englewood Cliffs, NJ.

Komar, P.D., 1979, Beach-slope dependence of longshore currents, Journal of the Waterway, Port, Coastal, and Ocean Division, Proceedings of the American Society of Civil Engineers, v.105, no.WW4, pp. 460-464.

Komar, P.D., 1987a, Selective grain entrainment by a current from a bed of mixed sizes: a reanalysis, Journal of Sedimentary Petrology, v.57, no.2, pp. 203-211.

Komar, P.D., 1987b, Selective gravel entrainment and the empirical evaluation of flow competence, Sedimentology, v.34, pp. 1165-1176.

Komar, P.D. and Clemens, K.E., 1986, The relationship between a grain's settling velocity and threshold of motion under unidirectional currents, Journal of Sedimentary Petrology, v.56, no.2, pp.258-266.

Komar, P.D. and Cui, B., 1984, The analysis of grain-size measurements by sieving and settling-tube techniques, Journal of Sedimentary Petrology, v.54, no.2, pp. 603-614.

Komar, P.D. and Gaughan, M.K., 1973a, Airy Wave Theory and Breaker Height Prediction, In: 13th Proceedings on Coastal Engineering.

Komar, P.D. and Inman, D.L., 1970, Longshore sand transport on beaches, Journal of Geophysical Research, v.75, no.30, pp. 5914-5927.

Komar, P.D. and Miller, M.C., 1973, The threshold of sediment movement under oscillatory water waves, Journal of Sedimentary Petrology, v.43, pp.1101-1.

Komar, P.D. and Miller, M.C., 1975, Reply: On the comparison between the threshold of sediment motion under waves and unidirectional currents with a discussion of the practical evaluation of the threshold: a discussion, Journal of Sedimentary Petrology, v.45, pp. 362-367.

Komar, P.D. and Wang, C., 1984b, Processes of selective grain transport and the formation of placers on beaches, Journal of Geology, v.92, pp. 637-655.

Kraft, J.C., 1971, Sedimentary environment facies patterns and geologic history of a Holocene marine transgression, Geologic Society of America Bulletin, v.82, pp. 2131-2158.

Kraus, N.C., 1987, Application of portable traps for obtaining point measurements of sediment transport rates in the surf zone, Journal of Coastal Research, v.3, pp. 139-152.

Kraus, N.C. and Dean, J.L., 1987, Longshore sediment transport rate distributions measured by trap, Coastal Sediments '87, WW Division, ASCE, New Orleans, LA.

Kraus, N.C. and Nakashima, L., 1986, Field Method for determining rapidly the weight of wet sand samples, Journal of Sedimentary Petrology, v.56, no. 4, pp.550-551.

Longuit-Higgins, M.S., 1970, Longshore Currents generated by obliquely incident sea waves, Journal of Geophysical Research, v.75, no.33, pp. 6788-6801.

Longuit-Higgins, M.S., 1971, Recent progress in the study of longshore currents, In: Waves on Beaches and Resulting Sediment Transport, Academic Press, New York.

Longuit-Higgins, M.S. and Steward, R.W., 1962, Radiation stress and mass transport in gravity waves with application to surf beats, Journal of Fluid Mechanics, v.13, pp. 481-504.

Longuit-Higgins, M.S. and Steward, R.W., 1964, Radiation stress in water waves; a physical discussion with applications, Deep Sea Research, v.11, no.4, pp. 529-563.

Lowry, W.D. and Baldwin, E.M., 1952, Late Cenozoic Geology of the Lower Columbia River valley, Oregon and Washington, Geological Society of America Bulletin, v.63, pp. 1-24.

Lutz, G.A., Hubbell, D.W., and Stevens, H.H. Jr., 1975, Discharge and flow distribution, Columbia River Estuary, U.S. Geological Survey Professional Paper 433-P, Washington D.C., 31 pp.

Lloyds (Lloyd's Register of Shipping), 1987, Register of Ships 1987-1988 (3 Volumes), Lloyd's Register of Shipping, London, UK.

Macdonald, E.H., 1983, Alluvial Mining The geology, technology, and economics of placers, Chapman and Hall, New York, 508pp.

Madsen, O.S. and Grant, W.D., 1975, The threshold of sediment movement under oscillatory waves: a discussion, Journal of Sedimentary Petrology, v.45, pp. 360-361.

Manohar, M., 1955, Mechanics of Bottom Sediment Movement Due to Wave Action, U.S. Army Corps of Engineers. Beach Erosion Board, Technical Memorandum no.75, 121p.

Mcdonald, E.H., 1983, Alluvial Mining, University Press, Cambridge, Chapman and Hall, NY, NY.

McKee, B., 1972, Cascadia, McGraw-Hill, Inc. New York.

Merchants Exchange, 1987-1988, Merchants Exchange Daily Ship Log (unpubl.), Merchants Exchange, Portland, OR.

Meyer, R.E.[Ed.], 1972, Waves on Beaches and Resulting Sediment Transport, Academic Presses, New York.

Michell, J.H., 1893, On the highest waves in water, Philosophical Magazine, 5th series, v.36, pp. 430-437.

Middleton, G.V. and Southard, J.B., 1978, Mechanics of Sediment Transport, Society of Economic Paleontologists and Mineralogists, Tulsa, OK.

Miller, M.C., McCave, I.N., and Komar, P.D., 1977, Threshold of sediment motion under unidirectional currents, Sedimentology, v.24, pp.507-527.

Muir Wood, A.M. and Fleming, C.A., 1981, Coastal Hydraulics 2nd Ed., Halsted Press, John Wiley & Sons, New York, 280 pp.

Newman, J.N., 1970, Recent Research on Ship Waves, pp.519-545; IN: Plesset, M.S., Yao-Tso Wu, T., and Doroff, S.W. (Eds.), Eighth Symposium Naval Hydrodynamics (Rome, Italy), Office of Naval Research, Department of Navy (U.S.A.), ACR-179.

Newton, R.S.,1968, Internal Structure of Wave-formed ripple marks in the nearshore zone,Sedimentology, v-11, pp.272-292.

NOAA, 1913, Columbia River Harrington Point to Grims Island 1:40,000 Plate, Soundings in feet, (National Oceanic and Atmospheric Administration), U.S. Department of Commerce, Washington D.C.

NOAA, 1985, Columbia River Harrington Point to Crims Island 1:40,000 Plate, Soundings in feet, (National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C..

Ofuya, A.O., 1970, Shore Erosion-Ship and Wind Waves, St. Claire, Detroit and St. Lawrence Rivers, Department of Public Works of Canada. Design Branch Report No.21, Marine Engineering Division.

Oregonian, 1987-1988, Port Calendar, (various dates), Oregonian Newspaper Business Section, Portland, OR.

Oswalt, N.R., Mellema, W.J., and Perry, E.B., 1981, Riverbank Erosion, Evaluation, Prevention and Control, Inland & Maritime Waterways & Ports, Section II Maritime Ports and Seaways, v.5, 25th International Navigation Congress, Edinburgh, pp.155-161.

Palmer, L.A., 1987, Personal Communication, Asst. Professor, Portland State University, Portland, OR.

Peterson, C.D., Komar, P.D., and Scheidegger, 1985, Distribution, Geometry, and Origin of heavy mineral placer deposits on Oregon beaches, Journal of Sedimentary Petrology, v.56, no.1, pp.67-77.

PIANC (Permanent International Association of Navigation Congresses), 1987, Guidelines for the design and construction of flexible revetments incorporating geotextiles for inland waterways, Report of Working Group 4 of the Permanent Technical Committee I, Supplement to Bulletin No.57, Brussels, Belgium.

Port of Portland, 1986, Guide to Navigation on the Lower Columbia.

Reading, H.G. [Ed.], 1978, Sedimentary Environments and Facies, Elsevier, New York.

Reed, W.E., Fever, R.L., and Moir, G.J., 1975, Depositional environment interpretation from settling-velocity (Psi) distributions, Geological Society of America Bulletin, v.86, pp. 1321-1328.

Robinson, L.S., 1897, Mechanical Propulsion on Canals, The Institution of Mechanical Engineers, Proceedings, Parts 1-2, Westminster, UK, pp. 148-167 and plates.

Roovers, P.P.L., Kerchkaert, P., Burgers, A., Noordam, A., and De Candt, P., 1981, Beach protection as part of the harbour extension at Zeebrugge, Belgium, Inland & Maritime Waterways & Ports, Section II Maritime Ports and Seaway, v.5, 25th International Navigation Congresses, Edinburgh, pp. 755-768.

Russell, J.S., 1834, Notice of the reduction of an anomalous fact in hydrodynamics, and of a new law of the resistance of fluids to the motion of floating bodies, Report of the 4th Meeting of the British Association for the Advancement of Science, John Murray, London, 1835, pp. 531-534.

Russell, J.S., 1835, On the solid of least resistance, Report of the 5th Meeting of the British Association for the Advancement of Science, John Murray, London, 1836, pp. 107-108.

Saunders, H.E., 1975, Hydrodynamics in Ship Design, vol.2, New York Society of Naval Architects and Marine Engineers.

Savage, R.P., 1953, Laboratory study of wave energy losses by bottom friction and percolation, Beach Erosion Board, Technical Memorandum 31, 25 p.

Schleyer, R., 1988, The goodness-of-fit to ideal Gauss and Rosin distributions: A new grain-size parameter - Reply, Journal of Sedimentary Petrology, v.58, no.5, pp. 917-918.

Scholle, P.A. and Spearing, D.(Eds.), 1982, Sandstone Depositional Environments, American Association Petroleum Geologists, Tulsa, OK, 410 pp.

Sherwood, C.R., Creager, J.S. (Principal Investigator), Roy, E.H., Gelfenbaum, G., and Dempsey, T., 1984, Sedimentary processes and environments in the Columbia River Estuary, Final CREDDP Report (Columbia River Estuary Data Development Program), CREST (Columbia River Estuary Study Taskforce), Astoria, OR., 318 p.

Shepard, F.P., 1963, Submarine Geology (2nd ed.), New York, Harper and Row.

Shields, A., 1936, "Anwendung der Aehnlichkeitsmechanik und Turbulenz forschung auf die Geschiebewegung, IN: Ott, W.P. & van Uchelen, J.C. (translators), California Institute of Technology, W.M. Keck laboratory of Hydraulics and Water Resources, Report No.167.

Simons, D.B. and Şentürk, F., 1976, Sediment Transport Technology, Water Resources Publications, Fort Collins, CO.

Sorensen, R.M., 1967, Investigation of Ship-Generated Waves, Journal of the Waterways and Harbors Division, ASCE, WW2, pp.85-99.

Sorensen, R.M, 1973, Water waves produced by ships, Journal of the Waterways, Harbors, and Coastal Engineering Division, WW2, ASCE, pp. 245-256.

Sorensen, R.M. and Weggel, J.R., 1984, Development of ship wave design information, chapter 216, Coastal Engineering Conference, ASCE.

Span, H.J.Th., Altink, H., Barends, F.J., Biemond, C., Biesheuvel, G.J., Huis in't Veld, J.C., Thanbet, R., Tutuarima, W.H., and Woestenenk, A.J., 1981, A review of relevant hydraulic phenomena and recent developments in research, design and construction of protective works, Inland & Maritime Waterways & Ports, Section II Maritime Ports and Seaways, v.5, 25th International Navigation Congress, Edinburgh, pp. 112-118.

Sundborg, Å. and Norrman, J., 1963, Güta Älv-Hydrologi och Morfologi, Med Särakild Hänsyn till-Erosionsprocesserna, Sveriges Geologiska Undersökning, Avhandlinger och Uppersatser, I4=0, ser. Ca., NR 43, Stockhom (in Swedish).

State of Maryland, 1949, Shore Erosion in Tidewater Maryland, reprint from Bulletin 6.

State of Maryland, 1981, The role of boat wakes in shore erosion in Anne Arundel County, Maryland, Maryland Coast Report no. 5.

State of Oregon, 1966-1984, Water Well Reports, Water Resources Department, Salem, OR.

State of Washington, 1973-1984, Water Well Reports, Department of Ecology, Olympia, WA.

State of Washington, 1985, Contract Provisions for Construction of SR 409 MP 3.32 to MP 2.65 PUGET ISLAND BRIDGE 409/10, Wahkiakum County, Department of Transportation, Olympia, WA.

Streeter, V.L. and Wylie, E.B., 1979, Fluid Mechanics, McGraw-Hill, Inc., pp.562.

Terzaghi, K. and Peck, R.B., 1967, Soil Mechanics in Engineering Practice, John Wiley and Sons, New York.

Thomson, W.(Lord Kelvin), 1887, On Ship Waves, Proceedings, Institute of Mechanical Engineers, Edinburgh, Great Britain, pp.409-433 and plates.

Thorne, C.R., MacArthur, R.C., and Bradley J.B., 1988, The Physics of Sediment Transport by Wind and Water, A Collection of Hallmark Papers by R.A. Bagnold, American Society of Civil Engineers, New York, 359 pp.

Thornton, E.B.,1973, Distribution of sediment transport across surf zone, Proc. 13th conf. on coast Engineering, pp.1049-68.

Tolan, T.L., Reidel, S.P., Beeson, M.H., Anderson, J.L., Fecht, K.R., and Swanson, D.A., 1987, Columbia River Basalt Group (CRBG): New Estimates of its Extent and Volume [abs. and poster], Abstracts of the 34th Annual Meeting of the Pacific Northwest Region of the American Geophysical Union, Olympia, WA.

Trask, P.D., 1939, Recent Marine Sediments A Symposium, The Amercian Association of Petroleum Geologists, Dover Publications, London.

USACE (U.S. Army Corps of Engineers), 1960, Lower Columbia River Bank Protection, Oregon and Washington, General Design Memorandum, plates 6,7,8, Engineering Division, Portland District, Portland, OR.

USACE (U.S. Army Corps of Engineers), 1961, Sedimentation Investigation Lower Columbia and Lower Willamette Rivers July 1959-August 1960, Portland District, Portland, OR.

USACE (U.S. Army Corps of Engineers), 1970-1986, Waterborne Commerce of the United States, Part 4: Waterways and Harbors Pacific Coast, Alaska, Hawaii, Water Resources Support Center, Fort Belvoir, VA.

USACE (U.S. Army Corps of Engineers), 1984, Shore Protection Manual, v.I, U.S. Army Coastal Engineering Research Center, Vicksburg, MI.

USACE (U.S. Army Corps of Engineers), 1985, Computer Program: Sinewaves (MACE-11) Linear Wave Theory Predictions, CERC Technical Note, CETN-I-32, Coastal Engineering Research Center), Burke, C.E., 7 p.

USACE (U.S. Army Corps of Engineers), 1986, Investigation of bank erosion at Sauvie Island, OR, Planning Division Technical Report, Portland District, Portland, OR.

USACE (U.S. Army Corps of Engineers), 1987, Environmental Engineering for Deep Draft Navigation Projects, EM 1110-2-1202, Engineer Manual.

USACE (U.S. Army Corps of Engineers), 1988a, Prediction of eroded versus accreted beaches, CERC Technical Note, CERC (Coastal Engineering Research Center), 7 p., Kraus, N. C. and Gingerich, K. J.

USACE (U.S. Army Corps of Engineers), 1988b, Maintenance Improvement Review Long Range Operational Plan, Lower Columbia River Dredging River Miles 32 to 48, Portland District, Portland, OR.

USACE (U.S. Army Corps of Engineers), 1988c, Dredging records, Navigation Branch, Operations Division, Portland District Office, Portland, Oregon, (unpubl.).

USACE (U.S. Army Corps of Engineers), 1988d, Flood analysis of the lower Columbia, Hydrology Section (Hydrologic and River Engineering section), Portland District, Portland, Oregon.

USACE (U.S. Army Corps of Engineers), 1989, Maintenance Improvement Review Long Range Operational Plan, Lower Columbia River Dredging River Miles 32 to 48, Portland District, Portland, OR.

USDI (U.S. Department of the Interior), 1947, The Columbia River, Prepared by Bureau of Reclamation, Michael W. Straus (Commissioner), R.J. Newell (Director, Region I).

USSCS (U.S. Soil Conservation Service), 1986a, Soil Survey of Columbia County, Oregon, U.S. Department of Agriculture, Washington, D.C., 197 pp.

USSCS (U.S. Soil Conservation Service), 1986b, Soil Survey of Grays Harbor County Area, Pacific County, and Wahkiakum County, Washington, U.S. Department of Agriculture, Washington, D.C., 296 pp.

Vanoni, V.A., 1975, Sedimentation Engineering, American Society of Civil Engineers, New York, New York.

Visher, G.S., 1969, Grain size distributions and depositional processes, Journal of Sedimentary Petrology, v.39, no.3, pp. 1074-1100.

Walpole, R.E. and Myers, R.H., 1985, Probability and Statistics for Engineers and Scientists, third ed., Macmillan Publishing Company, New York.

Walsh, T.J., 1987, Geologic Map of the Astoria and Ilwaco Quadrangles, Washington and Oregon, WA State Department of Natural Resources.

Waugh, R.G., 1971, Water depths required for ship navigation, Journal of Waterways, Harbors, and Coastal Engineering Division, WW3, ASCE, pp. 455-473.

West, D.O., 1987, Nature of shallow Cascadia Subduction Zone Paleoseismicity inferred from characteristics of Oregon-Washington coastline uplift [abs. and poster], Abstracts of the 34th Annual Meeting of the Pacific Northwest Region of the American Geophysical Union, Olympia, WA.

Whetton, J.T., Kelley, J.C., and Hanson, L.G., 1969, Characteristics of Columbia River sediment and sediment transport, Journal of Sedimentary Petrology, vol.39, no.3, pp. 1149-1166.

Yalin, M.S., 1972, Mechanics of Sediment Transport, Pergamon Press, New York.

APPENDIX A

SHORE PROFILES

This appendix presents study site profiles recorded during this study and the computer data files. Profiling is presented first for Price Island, then Puget Island, and finally Gull Island.

Price Island Study Site RK WA-55 Profile Data Base (ISRP)
DATA is in FEET

```
PR  1   81880629 1141 13 -420PRICELINE1     0  845   25  795   50  700   75  610
PR  1   82  100  520  150  380  200  240  225  160  250   60  261   10  275  -60
PR  1   83  291 -190  309 -420
PR  2   81880629 1115 15 -200PRICELINE2     0  939   25  950   50  930   75  930
PR  2   82   93  910   95  790   95  650   99  570  112  360  120  290  145  170
PR  2   83  170   60  195  -20  220 -110  245 -200
PR  3   81880629 1052 17 -370PRICELINE3     0  873   25  850   50  840   75  860
PR  3   82  100  790  113  700  114  690  116  610  120  540  139  330  164  210
PR  3   83  174  130  184   50  199  -30  224 -120  249 -240  268 -370
PR  4   81880629 1030 17 -490PRICELINE4     0 1270   10 1190   20 1120   28  730
PR  4   82   34  790   50  732   51  460   55  370   65  170   76   60  101   30
PR  4   83  126  -40  151  -90  201 -210  226 -280  251 -360  279 -490
PR  1   51870820 1332 13  -65PRICELINE1     0  845   25  765   50  755   75  705
PR  1   52  100  625  125  545  150  465  175  395  200  315  210  275  235  175
PR  1   53  260   55  280  -65
PR  2   51870820 1323 12 -110PRICELINE2     0  939   25  900   50  890   75  870
PR  2   52  100  860  125  830  150  740  175  700  200  440  225  240  250   50
PR  2   53  275 -110
PR  3   51870820 1306 13 -180PRICELINE3     0  873   25  800   50  790   75  820
PR  3   52  100  720  125  660  150  580  162  550  175  390  200  180  203  140
PR  3   53  228  -70  240 -180
PR  4   51870820 1249 16 -220PRICELINE4     0 1270   10 1190   20 1120   28  730
PR  4   52   34  790   50  732   75  690  100  680  125  620  150  510  175  360
PR  4   53  200  220  221   90  225   70  250  -80  275 -220
PR  1   61870909 1205 15 -510PRICELINE1     0  845   25  760   50  760   75  720
PR  1   62  100  640  125  540  150  460  175  380  200  310  225  230  250  140
PR  1   63  275   40  294 -120  319 -310  322 -510
PR  2   61870909 1156 15 -500PRICELINE2     0  939   25  900   50  880   75  860
PR  2   62  100  840  115  840  125  820  150  730  171  710  182    0  207  320
PR  2   63  232  140  257    0  293 -200  333 -500
PR  3   61870909 1144 14 -720PRICELINE3     0  873   25  820   50  800   75  830
PR  3   62  100  740  125  660  150  590  161  550  166  460  184  290  209  130
PR  3   63  234  -30  289 -280  314 -720
PR  4   61870909 1142 18 -760PRICELINE4     0 1270   10 1190   20 1120   28  730
PR  4   62   34  790   50  732   75  680  100  670  125  620  150  480  175  330
PR  4   63  200  190  225   20  250 -130  275 -240  305 -390  330 -550  342 -760
PR  1   71871003 1320 12 -140PRICELINE1     0  845   25  760   50  750   75  710
PR  1   72  100  630  125  530  150  440  175  370  181  350  241  170  281   20
PR  1   73  301 -140
PR  2   71871003 1340 13 -170PRICELINE2     0  939   25  900   50  880   75  860
PR  2   72  100  850  125  820  150  740  166  690  179  510  202  280  227  130
```

ISRP = Interactive Survey Reduction Program
(Birkemeier, 1988)

```
PR  2   73  252  -10  277 -170
PR  3   71871003 1350 15 -420PRICELINE3     0  873   25  810   50  790   75  740
PR  3   72  100  650  125  580  147  520  150  510  154  480  157  420  169  270
PR  3   73  194   80  219  -80  244 -270  253 -420
PR  4   71871003 1400 17 -410PRICELINE4     0 1270   10 1190   20 1120   28  730
PR  4   72   34  790   50  732   75  690  100  680  125  620  134  560  150  460
PR  4   73  175  320  200  260  210   80  235 -170  260 -310  281 -410
PR  3   41870727 1115 15 -607PRICELINE3     0  873   25  843   50  833   75  863
PR  3   42  100  763  125  693  150  603  175  593  181  563  200  293  225  113
PR  3   43  250 -117  270 -357  275 -437  286 -607
PR  4   41870727 1100 20 -678PRICELINE4     0 1270   10 1190   20 1120   28  730
PR  4   42   34  790   50  732   75  722  100  682  125  652  145  562  150  542
PR  4   43  175  412  200  282  225  152  250   32  275 -108  300 -278  323 -458
PR  4   44  325 -498  343 -678
PR  2   21870623 1120 13   89PRICELINE2     0  939   25  949   50  939   75  919
PR  2   22  100  899  125  889  150  819  175  779  200  699  225  599  250  479
PR  2   23  275  279  290   89
PR  3   21870623 1110 12  -37PRICELINE3     0  873   25  853   50  833   75  873
PR  3   22  100  783  125  693  150  623  175  573  200  563  225  243  250  -27
PR  3   23  252  -37
PR  4   21870623 1015 16 -248PRICELINE4     0 1270   10 1190   20 1120   28  730
PR  4   22   34  790   50  732   75  722  100  692  125  672  150  542  175  462
PR  4   23  200  372  225  272  250  152  275  -18  300 -248
PR  1   31870702 1035 13  -35PRICELINE1     0  845   25  765   50  755   75  725
PR  1   32  100  635  125  575  150  505  175  435  200  355  225  275  250  175
PR  1   33  275   45  284  -35
PR  2   31870702 1020 14   69PRICELINE2     0  939   25  909   50  899   75  879
PR  2   32  100  859  125  839  150  739  175  669  200  599  225  529  233  469
PR  2   33  234  389  250  269  275   69
PR  3   31870702 1012 12  -37PRICELINE3     0  873   25  833   50  813   75  793
PR  3   32  100  833  125  743  150  653  175  583  200  543  201  393  225  183
PR  3   33  249  -37
PR  4   31870702  931 16  -78PRICELINE4     0 1270   10 1190   20 1120   28  730
PR  4   32   34  790   50  732   75  692  100  652  125  642  150  542  175  432
PR  4   33  200  332  225  202  250   92  275  -48  279  -78
PR  1   41870727 1150 16 -495PRICELINE1     0  845   25  765   50  745   75  705
PR  1   42   90  665  100  625  125  555  150  475  175  405  200  335  225  275
PR  1   43  250  155  275    5  300 -175  309 -285  320 -495
PR  2   41870727 1130 17 -421PRICELINE2     0  939   25  949   50  919   75  909
PR  2   42  100  879  125  859  150  779  175  709  181  639  200  569  225  329
PR  2   43  250  149  275  -31  300 -221  317 -341  325 -421  337 -351
```

```
PR  1   11870615 1126 14 -235PRICELINE1     0  845   25  755   50  755   75  695
PR  1   12  100  625  125  565  150  505  175  455  200  385  225  285  250  145
PR  1   13  275   -5  300 -105  310 -235
PR  2   11870615 1112 14 -145PRICELINE2     0  939   25  939   50  949   75  929
PR  2   12  100  909  125  915  150  754  175  709  200  639  225  549  250  449
PR  2   13  275  319  300  165  321 -145
PR  3   11870615 1100 12 -127PRICELINE3     0  873   25  863   50  853   75  893
PR  3   12  100  793  125  713  150  643  175  593  200  553  225  423  250  173
PR  3   13  265  -23
PR  4   11870615 1142 17 -228PRICELINE4     0 1270   10 1190   20 1120   28  730
PR  4   12   34  790   50  732   75  672  100  682  125  672  150  552  175  492
PR  4   13  200  432  225  382  250  312  275  172  300  -58  320 -228
PR  1   21870623 1131 12   65PRICELINE1     0  845   25  765   50  755   75  705
PR  1   22  100  635  125  575  150  515  175  445  200  365  225  275  250  175
PR  1   23  269   65
```

Puget Island Study Site RK WA-62 Profile Data Base (ISRP)
Data entry= x z x z x z
where x=horizontal coordinate, 0 decimal places in FEET
z=vertical coordinate, 2 decimal places in FEET

```
PU  0   11880802 1120 30 -250PUGETLINE1W    0 1880   28 1850   53 1740   78 1570
PU  0   12  103 1280  108 1330  124 1840  144 1340  146 1160  166 1060  175 1150
PU  0   13  196  760  199  760  224  590  234  550  259  490  309  440  359  390
PU  0   14  409  350  459  300  509  260  559  210  595  120  611   20  661  -10
PU  0   15  711  -40  761  -90  771 -120  821 -210  846 -250
PU  1   11880321  954 22 -143PUGETLINE1W    0 1880   34 1820   64 1850   82 1900
PU  1   12   97 1940  107 1880  120 1650  124 1390  131  650  141  538  166  515
PU  1   13  191  510  216  492  257  432  308  311  333  138  342  188  364  104
PU  1   14  383  -15  409  -67  434  -97  459 -143
PU  1   21880607 1050 11  271PUGETLINE1W    0 1880   34 1820   64 1850   94 2070
PU  1   22  109 1750  121 1410  125  751  175  641  225  541  275  441  340  271
PU  1   31880617 1116 25 -115PUGETLINE1W    0 1880   34 1820   64 1850   69 1980
PU  1   32   84 2030  114 1660  125 1335  129  985  134  745  140  745  155  705
PU  1   33  165  755  183  755  189  705  214  675  264  595  314  465  339  385
PU  1   34  364  295  374  265  389  165  399   75  414  -15  426  -65  441 -115
PU  1   41880804 1019 13  055PUGETLINE1W    0 1880   34 1820   38 1960   88 1790
PU  1   42  113 1845  134  625  145  665  170  675  220  435  282  385  318  185
PU  1   43  343  105  368   55
PU  2   21880802 1452 21 -240PUGETLINE 2    0 2110   20 1810   28 2210   45 2140
PU  2   22   70 1670   98 1130  123  980  142  940  167 1070  180 1230  191 1120
PU  2   23  216  490  231  350  256  210  281  110  321  -50  338  -40  344   30
PU  2   24  369  -50  394  -80  408 -240
PU  3   11870731 0950 13 -140PUGETLINE 3    0 2082   12 2100   24 2150   49 2000
PU  3   12  150 1600  165 1000  175  650  177  550  197  350  247  200  267  120
PU  3   13  273  060  293 -140
PU  3   21880321 1021 16 -242PUGETLINE 3    0 2082   12 2112   24 2262   49 2002
PU  3   22   53 1522   59  542   84  468  109  497  159  442  194  385  228  306
PU  3   23  253  246  303  111  341    6  363 -100  388 -242
PU  3   31880607 1100 10  202PUGETLINE 3    0 2082   10 2260   20 2302   30 2242
PU  3   32   45 2042   63  602  113  552  163  492  213  392  278  202
PU  3   41880617 1140 19   26PUGETLINE 3    0 2082   10 2060   21 2070   41 2620
PU  3   42   71 2190   78 1750   81 1200   86  941   91  890  101  803  126  723
PU  3   43  176  674  201  641  251  520  301  383  376  183  401  137  426   41
PU  3   44  445  -76
PU  4   11880617 1116 14 -519PUGETLINE 4    0 2160   22 2210   37 2360   67 2320
PU  4   12   78 1230   88  680  113  605  163  546  213  456  263  319  313  199
PU  4   13  363   65  385 -113  410 -259
PU  4   21880802 1502 11  290PUGETLINE 4    0 2160   26 2160   31 2370   41 2450
PU  4   22   65 2030   68 1480  193 1400  268 1190  280  630  295  420  385   90
PU  4   31880804 1035 13  220PUGETLINE 4    0 2160   26 2160   31 2420   40 2450
PU  4   32   65 2000   78 1490  178 1460  263 1220  273  870  274  670  279  630
```

ISRP = Interactive Survey Reduction Program
(Birkemeier, 1988)

```
PU  4   33  297  440  364  220
PU  5   11870731 1010 11 -100PUGETLINE 5    0 2280   20 2250   40 2100   70 2200
PU  5   12  200 2100  215 1500  225  800  227  700  250  400  300   50  320 -100
PU  5   21880607 1112  9  440PUGETLINE 5    0 2280   20 2260   40 2220   60 2210
PU  5   22   85 2130  106  760  156  590  206  510  237  440
PU  5   31880617 1155 11   00PUGETLINE 5    0 2280   10 2270   78 2180   86 1380
PU  5   32   98  760  148  610  194  530  244  410  294  300  344  150  379   00
PU  7   11870723 1057 15  -40PUGETLINEA    0 1680   10 1700   16 1610   31 1730
PU  7   12   56 1500   67 1260   84 1210  100  800  125  710  150  640  164  490
PU  7   13  189  260  214   60  249  -10  269  -40
PU  7   21870731 1020 18 -520PUGETLINEA    0 1680   10 1700   16 1610   18 1570
PU  7   22   27 1870   77 1640  127 1450  177 1240  215 1060  227  680  229  540
PU  7   23  248  370  298  190  318  110  324   40  342 -260  354 -420  364 -520
PU  7   31870821 1046 19 -510PUGETLINEA    0 1680   10 1700   13 1660   16 1610
PU  7   32   28 1780   31 1730   53 1730  128 1410  175 1250  205 1060  217  630
PU  7   33  227  460  237  360  287  230  316  -30  336 -170  354 -310  364 -410
PU  7   34  381 -510
PU  7   41870911  954 16 -350PUGETLINEA    0 1680   10 1700   16 1610   26 1810
PU  7   42   31 1730   38 1790  122 1430  172 1260  196 1120  203  960  204  690
PU  7   43  216  370  252  200  286   20  322 -150  354 -350
PU  7   51880120 1017 15  -70PUGETLINE A    0 1680   10 1700   16 1610   21 1730
PU  7   52   30 1710   70 1640  110 1510  155 1380  157  830  158  720  160  610
PU  7   53  180  280  190  110  210  -30  225  -70
PU  7   61880321 1106 15 -250PUGETLINE A    0 1680   10 1700   55 1780   85 1600
PU  7   62  105 1480  119 1480  129  650  138  374  148  236  152  140  177   81
PU  7   63  202   50  227  -14  277 -146  287 -250
PU  7   71880607 1123 13   70PUGETLINE A    0 1680   10 1700   16 1610   31 1730
PU  7   72   70 1600  112 1400  115  570  122  410  130  250  139  230  189  170
PU  7   73  214  100  229   70
PU  7   81880617 1217 14 -200PUGETLINE A    0 1680   10 1650   25 1610   40 1630
PU  7   82   65 1580   90 1490  104 1380  106  800  109  570  112  480  132  270
PU  7   83  207  140  257   20  313 -200
PU  7   91880804 1139 14     PUGETLINE A    0 1680   10 1650   15 1570   60 1700
PU  7   92  105 1450  150 1470  195 1440  252 1470  266  670  286  490  336  280
PU  7   93  386   70  411   10  436  -40
PU  8   11870723 1256 11  100PUGETLINEB    0 1600    5 1680   10 1820   29 1500
PU  8   12   42  860   67  740   92  610  117  470  142  380  167  260  181  100
PU  8   21870731 1115 18 -510PUGETLINEB    0 1600    5 1680   10 1820   13 1620
PU  8   22   29 1500   63 1350  113 1350  138 1240  150  790  171  580  189  400
PU  8   23  204  300  219  260  250  120  261  -20  281 -280  294 -410  309 -510
PU  8   31870821 1134 16 -250PUGETLINEB    0 1600    5 1680   10 1820   14 1620
```

```
PU  8   32   29 1500   64 1360   89 1390  100 1370  133 1310  143 1140  158  720
PU  8   33  198  320  236  160  262   60  284 -150  291 -250
PU  8   41880120 1028 12   40PUGETLINE B    0 1600    5 1680   10 1820   29 1500
PU  8   42   50 1470   98 1390  118 1370  120  790  140  460  175  210  195  130
PU  8   43  215   40
PU  8   51880321 1114 20 -303PUGETLINE B    0 1600    5 1680   10 1820   15 1580
PU  8   52   29 1500   45 1370   65 1340   88 1330   92  650  100  446  101  398
PU  8   53  113  234  120  120  145   76  161   54  186  -23  198  -73  214 -120
PU  8   54  239 -226  254 -303
PU  8   61880607 1131 13    0PUGETLINE B    0 1600    5 1680   10 1820   12 1560
PU  8   62   29 1500   72 1280   77  540   84  370   92  180   97  120  122  100
PU  8   63  157   40  172   00
PU  8   71880617 1000 15 -100PUGETLINE B    0 1600    5 1680   10 1820   14 1570
PU  8   72   39 1420   64 1330   66 1310   68  680   69  600   72  530   73  490
PU  8   73   93  240  143  100  193  000  253 -200
PU  8   81880804 1144 12  130PUGETLINE B    0 1600    5 1680   10 1820   14 1660
PU  8   82   29 1550  119 1480  198 1470  211  860  236  610  258  560  348  290
PU  8   83  398  130
PU  9   11870723 1308 13   50PUGETLINEC     0 1480   10 1430   35 1370   39 1370
PU  9   12   48  910   73  730   98  600  123  490  148  430  173  330  193  270
PU  9   13  218  150  241   50
PU  9   21870821 1206 15 -340PUGETLINEC     0 1480   10 1430   35 1370   60 1380
PU  9   22  110 1340  150 1370  160 1330  170 1180  179  630  189  480  204  380
PU  9   23  227  160  265  -40  282 -240  303 -340
PU  9   31880120 1042 13  -40PUGETLINE C    0 1480   10 1430   35 1370   70 1380
PU  9   32  110 1350  150 1390  151  980  155  700  175  430  195  260  331  170
PU  9   33  351   70  371  -40
PU  9   41880321 1122 19 -379PUGETLINE C    0 1480   10 1430   35 1370   70 1360
PU  9   42  100 1310  120 1320  134 1360  137  560  139  480  145  363  146  317
PU  9   43  158  235  169  -41  194 -196  219 -134  244 -169  262 -206  287 -275
PU  9   44  312 -379
PU  9   51880607 1141  9   60PUGETLINE C    0 1480   10 1480   80 1400  122 1420
PU  9   52  125  620  131  490  138  240  143  140  155   60
PU  9   61880617 1246 18 -120PUGETLINE C    0 1480   10 1480   25 1440   50 1450
PU  9   62   63 1490   88 1430  113 1420  120 1320  123  830  125  650  127  610
PU  9   63  128  550  141  340  161   70  162   50  166   30  216  -30  231 -120
PU  9   71880804 1152 11 -270PUGETLINE C    0 1480   10 1480   25 1440   31 1390
PU  9   72   91 1380  151 1370  215 1370  227  590  252  350  314   00  339 -270
PU 10   11870723 1322 15  100PUGETLINED     0 1490   10 1540   20 1460   31  860
PU 10   12   56  810   64  780   76  540  101  470  126  430  151  410  176  370
PU 10   13  201  320  205  290  230  180  242  100
```

```
PU 10   21870731 1225 13 -660PUGETLINED     0 1490   10 1540   60 1470  110 1390
PU 10   22  163 1360  176  570  201  390  251  290  276  220  289  120  311 -160
PU 10   23  336 -560  367 -660
PU 10   31870821 1232 14 -270PUGETLINE D     0 1490   10 1540   85 1410  135 1450
PU 10   32  155 1350  161 1260  172  600  184  470  197  400  241  220  278   30
PU 10   33  296  -70  321 -170  326 -270
PU 10   41870911 1008 15 -370PUGETLINED     0 1490   10 1540   70 1435   94 1400
PU 10   42  136 1450  148 1390  160 1250  164 1050  165  570  175  450  193  370
PU 10   43  221  200  267   30  303 -210  315 -370
PU 10   51880120 1054 11    0PUGETLINE D     0 1490   10 1540   70 1430  133 1460
PU 10   52  150 1370  152  790  172  500  192  320  216  190  236   70  247    0
PU 10   61880321 1028 13 -230PUGETLINE D     0 1490   10 1540   60 1430  100 1450
PU 10   62  146 1320  149  650  153  590  168  370  180  230  193  090  243  -80
PU 10   63  256 -130  281 -230
PU 10   71880607 1148  9  -40PUGETLINE D     0 1490   10 1505  100 1380  133 1430
PU 10   72  139  560  147  410  164  160  172   20  176  -40
PU 10   81880617 1130 12  670PUGETLINE D     0 1490   10 1510  114 1350  128 1400
PU 10   82  131 1300  133  670  136  500  138  340  139  290  150  110  180 -120
PU 10   83  185 -220
PU 10   91880804 1156  8 -280PUGETLINE E     0 1490   10 1510  220 1410  234  550
PU 10   92  259  260  284  090  296  -50  316 -280
PU 11   11870723 1336 12 -378PUGETLINEE     0 1600   10 1580   17 1500   27  850
PU 11   12   52  740   77  630  102  510  127  450  152  350  168  310  193  210
PU 11   13  213  130
PU 11   21870731 1241 14 -650PUGETLINEE     0 1600   10 1550   17 1440   42 1460
PU 11   22  142 1460  166 1360  178  740  186  610  198  540  248  150  286 -050
PU 11   23  319 -270  340 -450  375 -560
PU 11   31870821 1340 15 -170PUGETLINEE     0 1600   10 1550   35 1470   85 1470
PU 11   32  125 1500  140 1440  150 1360  166 1280  181  460  191  370  197  320
PU 11   33  224  130  241   30  257  -70  269 -170
PU 11   41880120 1105 11   40PUGETLINE E     0 1600   10 1550   20 1550   80 1470
PU 11   42  148 1400  154 1310  158  820  198  340  209  240  229   70  234   40
PU 11   51880321   11  8  700PUGETLINE E     0 1600   10 1550   16 1430   76 1420
PU 11   52  131 1480  151 1310  154 1070  159  700
PU 11   61880607 1227 10 -100PUGETLINE E     0 1600   10 1550   76 1420  125 1500
PU 11   62  147 1330  159  720  184  420  209  210  223   80  248 -100
PU 11   71880617 1200 12  790PUGETLINE E     0 1600   10 1540   15 1510   17 1440
PU 11   72   22 1470   47 1460   94 1430  104 1460  126 1500  142 1390  146 1230
PU 11   73  153  790
PU 11   81880804 1206  9 -360PUGETLINE E     0 1600   10 1540   88 1500   90 1550
PU 11   82  243 1560  259 1590  284 1240  302   00  322 -360
```

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PU 12   11870723 1408 11  200PUGETLINEF     0 2060   10 2040   48 1430   55  620
PU 12   12   87  670   88  480  113  480  138  410  149  360  174  250  195  200
PU 12   21870731 1315 13 -620PUGETLINEF     0 2060   10 2040   30 1650   55 1560
PU 12   22  155 1500  189 1490  203  560  220  370  270  120  295   40  306 -120
PU 12   23  320 -520  340 -620
PU 12   31870821 1412 18 -120PUGETLINEF     0 2060   10 2040   30 1650   60 1520
PU 12   32   85 1490  110 1510  135 1480  160 1540  170 1520  176 1490  188 1250
PU 12   33  198  670  208  520  232  370  258  180  275   80  291  -20  303 -120
PU 12   41870911 1024 18 -468PUGETLINEF     0 2060   10 2040   30 1650   60 1520
PU 12   42   96 1480  120 1460  142 1430  171 1480  183 1340  190 1150  199  800
PU 12   43  200  600  212  430  224  340  270   37  294 -258  306 -368  310 -468
PU 12   51880120 1114 12  100PUGETLINE F     0 2060   10 2040   30 1650   60 1520
PU 12   52  120 1500  171 1510  185 1300  191  840  211  580  231  380  240  290
PU 12   53  260  100
PU 12   61880321 1225 14 -273PUGETLINE F     0 2060   10 2040   30 1650   50 1520
PU 12   62  110 1500  170 1520  183 1350  184 1200  190  810  199  650  224  390
PU 12   63  244  230  282 -110  307 -310
PU 12   71880607 1237 12  -60PUGETLINE F     0 2060   10 2040   30 1650   60 1520
PU 12   72  110 1500  162 1500  172 1330  182  770  207  480  232  260  245  140
PU 12   73  270  -60
PU 12   81880617 1407 16  -30PUGETLINE F     0 2060   10 2040   30 1650   48 1520
PU 12   82   73 1490   98 1500  104 1500  123 1470  141 1550  166 1440  172 1280
PU 12   83  181  790  191  650  216  390  219  330  262  -30
PU 12   91880804 1310 18 -350PUGETLINE F     0 2060   10 2040   30 1650   60 1520
PU 12   92  135 1470  153 1570  161 1540  165 1200  176 1200  181 1110  231 1110
PU 12   93  263 1050  288 1240  294 1230  306  500  356  180  378 -100  390 -350
PU 13   11870723 1431  7  360PUGETLINEG     0 1410   10 1450   26 1510   37 1130
PU 13   12   39 1170   49  590   62  360
PU 13   21870731 1340 14 -660PUGETLINEG     0 1410   10 1450   35 1470  110 1470
PU 13   22  170 1530  184  640  185  520  195  410  235  130  245   30  248   20
PU 13   23  259 -130  275 -520  303 -660
PU 13   31870821 1430 12  -40PUGETLINEG     0 1410   10 1450   35 1470   85 1420
PU 13   32  115 1460  165 1410  173 1150  182  620  206  340  230  160  255   60
PU 13   33  264  -40
PU 13   41880120 1125 10  140PUGETLINEG     0 1410   10 1450   35 1470   70 1480
PU 13   42  138 1510  164 1370  168  870  188  590  211  330  229  140
PU 13   51880321 1230 17 -284PUGETLINE G     0 1410   10 1450   35 1470   60 1460
PU 13   52  120 1440  150 1500  164 1430  165 1300  173  790  184  628  187  589
PU 13   53  199  588  201  542  226  292  251   56  269 -126  284 -284
PU 13   61880607 1235 11  -60PUGETLINE G     0 1410   10 1450   35 1470  135 1510
PU 13   62  155 1490  164 1030  168  800  181  610  206  340  230  140  247  -60
```

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PU 13   71880617 1412 13  -90PUGETLINE G    0 1410   10 1450   35 1470   75 1490
PU 13   72  113 1460  134 1500  154 1490  161 1270  168  670  177  550  202  260
PU 13   73  252  140  277  -90
PU 13   81880804 1329 13 -190PUGETLINE G    0 1410   10 1450   21 1510   71 1480
PU 13   82  138 1500  156 1480  158 1040  164  600  229  550  243  600  268  470
PU 13   83  315   20  330 -190
PU 14   11870723 1448  9  200PUGETLINEH    0 1510   10 1570   85 1420   92 1440
PU 14   12  117 1460  129 1380  142  560  154  370  167  200
PU 14   21870731 1430 15 -550PUGETLINEH    0 1510   10 1570   50 1520   75 1460
PU 14   22  100 1520  185  620  241  570  242  530  255  320  257  250  267   60
PU 14   23  268    0  271  -50  285 -450  290 -550
PU 14   31870821 1448 15  -30PUGETLINEH    0 1510   10 1570   60 1510   79 1460
PU 14   32   98 1560  123 1320  148 1140  158 1050  173  870  193  670  218  580
PU 14   33  245  370  264  270  282   70  289  -30
PU 14   41870911 1038 14 -390PUGETLINEH    0 1510   10 1570   35 1490   37 1510
PU 14   42   81 1440   93 1540  105 1480  153 1080  171  880  219  500  223  350
PU 14   43  231  230  261   10  276 -390
PU 14   51880120 1137 11  100PUGETLINEH    0 1510   10 1570   80 1440   95 1530
PU 14   52  135 1220  175  780  195  510  215  330  235  170  240  130  260  -04
PU 14   61880321 1233 11 -270PUGETLINE H    0 1510   10 1570   54 1430   87 1500
PU 14   62  117 1200  177  710  207  460  232  240  241  180  278 -150  298 -270
PU 14   71880607 1240 11 -170PUGETLINE H    0 1510   10 1570   77 1430  110 1280
PU 14   72  160  880  180  680  202  500  227  280  257   30  272 -110  278 -170
PU 14   81880617 1300 11 -040PUGETLINE H    0 1510   10 1570  100 1470  125 1180
PU 14   82  150  980  175  750  189  610  200  490  225  280  238  170  262 -040
PU 14   91880804 1338 10 -360PUGETLINE H    0 1510   07  460   75  460   90 1420
PU 14   92  150  940  210  330  230  010  295 -210  320 -320  330 -430
PU 15   11870731 1445 14 -440PUGETLINE1    0 1610   10 1670   50 1440  100 1230
PU 15   12  185 1080  202  880  216  530  241  380  261  240  286  120  292   30
PU 15   13  323  -90  332 -240  337 -440
PU 15   21870826 1350 13 -260PUGETLINE1    0 1610   10 1670   50 1440  100 1280
PU 15   22  150 1160  197 1040  204  760  208  680  233  450  258  290  268  220
PU 15   23  302  -60  314 -260
PU 15   31870911 1050 15 -443PUGETLINE1    0 1610   10 1670   50 1440  100 1277
PU 15   32  172 1117  200  957  205  797  209  697  212  657  241  407  258  337
PU 15   33  291  117  303   -3  327 -263  334 -443
PU 15   41880120 1149 11  250PUGETLINE 1    0 1610   10 1670   50 1440  100 1210
PU 15   42  160 1050  180 1020  200  930  201  850  221  590  242  400  262  250
PU 15   51880321 1242 12 -160PUGETLINE 1    0 1610   10 1670   50 1440  100 1210
PU 15   52  175 1030  199  950  200  820  230  470  260  250  272  160  303 -110
PU 15   53  318 -240
```

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PU 15   81880607 1244  9   67PUGETLINE I     0 1610   10 1670   50 1440  100 1210
PU 15   62  195  917  205  707  255  247  272  157  292   07
PU 15   71880804 1353  9 -260PUGETLINE I     0 1610    7  460   75  460   90 1156
PU 15   72  100 1140  180 1020  255  220  275 -170  290 -360
PU 16   11870731 1500  9 -320PUGETLINEJ     0 1430   10 1410   63 1170  138  690
PU 16   12  188  600  194  190  204   70  241 -290  247 -390
PU 16   21870828 1337 12 -320PUGETLINEJ     0 1430   10 1410   60 1260   85 1050
PU 16   22  110  930  143  700  168  550  193  400  218  240  230  160  255  -90
PU 16   23  273 -320
PU 16   31880120 1157  9  280PUGETLINE J     0 1430   10 1410   80 1080  100  990
PU 16   32  120  840  140  720  160  600  181  470  201  280
PU 16   41880321 1248 12 -200PUGETLINE J     0 1430   10 1410   67 1220   92 1023
PU 16   42  119  836  154  622  176  485  201  346  221  248  246   37  255  -55
PU 16   43  270 -200
PU 17   11870802 1612 10  120PUGETLINEK     0 1164   10 1164   25 1284   60 1050
PU 17   12  100 1036  129  590  130  560  162  210  168  090  180 -190
PU 17   21870828 1324 13 -220PUGETLINEK     0 1164   10 1164   25 1284   50 1154
PU 17   22   75 1184   93 1184   98 1154  122  734  129  634  154  334  167  154
PU 17   23  192 -156  195 -296
PU 17   31870911 1106 13 -510PUGETLINEK     0 1164   10 1164   25 1284   50 1034
PU 17   32   98 1044  114  764  117  714  118  674  121  604  136  404  148  274
PU 17   33  176  -96  200 -510
PU 17   41880120 1205 10  250PUGETLINE K     0 1164   10 1164   25 1284   40 1104
PU 17   42   85 1084  103  984  104  874  124  584  131  454  151  254
PU 17   51880321 1251 13 -220PUGETLINE K     0 1164   10 1164   25 1284   42 1124
PU 17   52   63 1044   99 1044  106  974  108  874  120  634  140  400  161  184
PU 17   53  186  -64  197 -220
PU 17   61880607 1257 12 -460PUGETLINE K     0 1164   10 1164   25 1284   60 1034
PU 17   62   95 1000  100  944  103  804  113  634  138  354  166   84  176  -60
PU 17   63  182 -106
PU 17   71880804 1407  9 -380PUGETLINE K     0 1164   10 1164  100 1100  150  930
PU 17   72  181  910  185  520  210  130  242 -110  254 -380
PU 18   11870802 1630  9  -70PUGETLINEL     0 1450   10 1430   37 1200   39 1110
PU 18   12  102 1010  127  630  128  430  153  130  171  -70
PU 18   21870826 1309 14 -550PUGETLINEL     0 1450   10 1430   37 1200   62 1060
PU 18   22   77 1050   92 1070  114  860  117  700  121  630  122  590  147  270
PU 18   23  163   50  188 -320  193 -550
PU 18   31880120 1212  9  320PUGETLINE L     0 1450   37 1200   62 1060   92 1070
PU 18   32   98 1030  100  870  120  580  127  510  142  320
PU 18   41880321 1258 14 -205PUGETLINE L     0 1450   10 1430   37 1200   62 1060
PU 18   42   92 1069   97 1038  100  847  101  824  102  779  107  673  132  362
```

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PU 18   43  140  242  165  -33  180 -205
PU 18   51880607 1256  9   20PUGETLINE L    0 1450   10 1430   37 1200   62 1060
PU 18   52   94 1040   99  750  119  470  141  190  156   20
PU 19   11870826 1252 14 -460PUGETLINE H    0 1170   10 1070   20 1100   35 1080
PU 19   12   50 1160   60 1110   81  820   91  620  106  430  120  300  140   80
PU 19   13  144    0  162 -260  168 -460
PU 19   21880321 1300 11 -130PUGETLINE H    0 1170   10 1070   20 1100   50 1160
PU 19   22   61 1120   67  680   82  470   92  360  107  170  122   20  139 -130
PU 19   31880607 1305 10  -70PUGETLINE H    0 1170   10 1070   20 1100   50 1150
PU 19   32   52  830   56  650   71  410   90  120  100  -10  105  -70
PU 19   41880804 1420        PUGETLINE H    0 1170   10 1070   14  940   64  850
PU 19   42   84  720   87  570  105  380  125  -30  135 -220
PU 20   11870826 1217 17 -250PUGETLINEN    0 1070   10 1070   11 1080   12  810
PU 20   12   13  750   25  620   31  560   50  470   75  360  110  240  137   60
PU 20   13  139    0  145   40  155   40  158  -30  178 -120  256 -250
PU 20   21870911 1125 15 -431PUGETLINEN    0 1070   10 1070   11 1080   12  830
PU 20   22   22  650   34  570   78  400  104  340  108  280  111  180  234  120
PU 20   23  235   50  262  -31  274 -191  474 -431
PU 20   31880321 1310  9 -630PUGETLINE N    0 1070    2  450    3  196   13   22
PU 20   32   38 -136   75 -274  100 -336  125 -490  139 -630
PU 21   11870826 1158 14 -250PUGETLINEO    0  980   10 1000   28 1170   34  690
PU 21   12   46  490   56  430   81  360  106  280  131  230  141  150  156   20
PU 21   13  206 -130  220 -160  277 -250
PU 21   21870911 1140 13 -446PUGETLINEO    0  980   10 1000   28 1170   34  784
PU 21   22   50  544   87  454  143  334  147  164  171   24  207  -36  219  -66
PU 21   23  363 -296  411 -446
PU 21   31880321 1314 11  -40PUGETLINE O    0  980   10 1000   22  980   23  820
PU 21   32   36  600   49  480   74  420   93  320  143  260  146   70  163  -40
PU 21   41880607 1310  8   70PUGETLINE O    0  980   10 1000   19 1120   20  830
PU 21   42   40  560  135  430  153  180  173   70
```

Gull Island Study Site RK OR-88.5 Profile Data Base (ISRP)
DATA is in FEET

```
GU  1  11870728 1100 14  -20GULL LINEAW    0 1910   10 1890   25 1880   40  830
GU  1  12   65  450   90  180  115   60  140   50  165   20  190   10  215   20
GU  1  13  250    0  265  -10  290  -20
GU  1  21870806 1728 12 -110GULL LINEAW    0 1910   10 1890   26 1860   42  700
GU  1  22   60  500   86  270  111  -30  136  -60  161  -80  186 -100  211 -100
GU  1  23  236 -110
GU  1  31870818 1000 17  -30GULL LINEAW    0 1910   10 1890   25 1890   41  780
GU  1  32   62  500   82  360   92  240  117   70  142   50  167   20  192   20
GU  1  33  217   10  242    0  267  -10  292  -10  317  -20  342  -30
GU  1  41870824 1055 11   40GULL LN A-W    0 1950   25 1920   43  830   46  770
GU  1  42   56  600   66  520   97  240  107  140  124  100  174   50  224   40
GU  1  51870930 1045 10   30GULL LN A-W    0 1910   10 1900   25 1870   40  780
GU  1  52   53  570   71  370   96  190  121   90  146   40  171   30
GU  1  61880119 1028  7  300GULL LN A-W    0 1910   10 1890   25 1890   30 1010
GU  1  62   55  640   69  460   86  300
GU  1  71880622 1021 12  220GULL LN A-W    0 1910   10 1890   23 1870   24 1550
GU  1  72   34  950   41  830   43  790   57  600   60  550   73  410   75  370
GU  1  73   92  220
GU  2  11870728 1130 11 -300GULL LN A-N    0 1910   10 1960   32 2120   63  820
GU  2  12   88  430  116  120  141   30  166  -30  191  -90  216 -180  228 -300
GU  2  21870806 1720 10 -200GULL LN A-N    0 1910   10 1970   30 2120   70  680
GU  2  22  120  650  220  560  274  420  294  270  316    0  322 -200
GU  2  31870818 1025 15 -210GULL LN A-N    0 1910   10 1970   30 2120   60  790
GU  2  32   80  660  130  650  187  620  199  550  224  560  249  500  287  410
GU  2  33  300  280  310  150  326 -110  328 -210
GU  2  41870824 1040 18 -340GULL LN A-N    0 1950   10 1970   30 2140   66  800
GU  2  42   91  700  106  700  116  780  191  630  196  610  201  580  251  570
GU  2  43  301  590  309  560  329  470  354  220  360  100  376 -170  381 -340
GU  2  51870930 1044  9  290GULL LN A-N    0 1910   10 1970   29 2100   54  820
GU  2  52   79  660  129  600  239  520  254  380  266  290
GU  2  61880119 1045 15  300GULL LN A-N    0 1910   10 1960   30 2080   42 1600
GU  2  62   44 1050   69  840   94  690  119  660  144  640  169  630  194  630
GU  2  63  219  570  237  490  262  350  282  300
GU  2  71880622 1030 11  220GULL LN A-N    0 1910   10 1970   28 2100   35 1720
GU  2  72   58  970   83  820  123  780  173  560  205  370  230  280  255  220
GU  3  11870728 1207  9 -240GULL LINE B    0 2060   10 1972   60 2110  140 1700
GU  3  12  154  880  179  480  208  130  258 -100  279 -240
GU  3  21870806 1711 14 -190GULL LINE B    0 2060   10 2050   60 2110  100 1700
GU  3  22  115 1300  125 1170  150 1110  200  930  250  710  300  530  330  410
GU  3  23  338  290  353  -90  357 -190
GU  3  31870818 1046 12  600GULL LINE B    0 2060   10 2050   55 2150  102 1720
```

ISRP = Interactive Survey Reduction Program
(Birkemeier, 1988)

```
GU  3   32  119 1250  144 1130  194 1050  204  870  214  690  252  650  268  640
GU  3   33  270  600
GU  3   41870824 1110 19 -490GULL LINE B    0 2060   10 2050   60 2010  100 1700
GU  3   42  102 1650  118 1210  143 1060  218  900  243  830  268  700  268  640
GU  3   43  297  610  322  480  327  440  337  330  358  130  366   10  376 -190
GU  3   44  386 -490
GU  3   51870930 1057 14  210GULL LINE B    0 2060   10 2050   60 2030   61 2070
GU  3   52   96 1710  111 1240  186 1030  236  840  261  730  286  710  292  600
GU  3   53  318  440  328  310  338  210
GU  3   61880119 1050 10  330GULL LINE B    0 2060   10 2050   60 2010   90 1660
GU  3   62  100 1710  125 1140  185  990  230  830  265  520  290  330
GU  3   71880622 1043 22  210GULL LN A-N    0 2060   10 2040   35 1990   48 2000
GU  3   72   53 2040   65 1970   90 1740  101 1710  110 1410  116 1290  131 1120
GU  3   73  156 1090  181 1010  206  920  231  900  241  890  253  810  268  640
GU  3   74  273  580  286  460  292  360  317  210
GU  4   11870728 1305 10 -420GULL LINE C    0 2020   10 1950   85 1520  126 1210
GU  4   12  148 1240  159  880  184  470  199  -30  244 -270  259 -420
GU  4   21870806 1651 13 -210GULL LINE C    0 2020   10 1960  100 1420  150 1160
GU  4   22  200 1190  270 1200  288  820  300  760  347  610  357  530  373  290
GU  4   23  393  -10  463 -210
GU  4   31870818 1105 14 -140GULL LINE C    0 2020   10 1960  100 1430  150 1160
GU  4   32  225 1200  270 1210  288  850  351  600  356  530  371  420  379  340
GU  4   33  397  160  419  -40  426 -140
GU  4   41870824 1125 15 -430GULL LINE C    0 2020   10 1960  100 1420  175 1200
GU  4   42  250 1170  270 1210  288  830  313  710  336  680  346  580  358  500
GU  4   43  393  190  403   60  419 -260  426 -430
GU  4   51870930 1108 16  -90GULL LINE C    0 2020   10 1960  100 1430  125 1240
GU  4   52  150 1170  200 1190  239 1170  267 1210  280  810  296  720  317  720
GU  4   53  340  520  350  520  375  120  390  -10  393  -90
GU  4   61880119 1055 10  260GULL LINE C    0 2020   10 1960  100 1440  160 1180
GU  4   62  260 1220  270 1170  271 1060  296  860  326  530  341  260
GU  4   71880622 1110 18  220GULL LINE C    0 2020   10 1970   78 1580  128 1230
GU  4   72  153 1160  178 1200  203 1200  253 1190  271 1200  275 1140  282 1010
GU  4   73  294  900  307  770  312  660  317  600  328  480  342  360  360  220
GU  5   11870728 1323 12 -400GULL LINE D    0 2060   10 1930   85 1420  135 1180
GU  5   12  142 1270  175 1180  181 1030  219  420  247   40  287 -210  297 -340
GU  5   13  303 -400
GU  5   21870806 1637 15 -140GULL LINE D    0 2060   10 1930   72 1510  100 1300
GU  5   22  168 1150  200 1170  250 1180  275 1040  305  750  355  630  400  410
GU  5   23  430  330  463  160  471  -40  476 -140
GU  5   31870818 1122 16 -150GULL LINE D    0 2060   10 1930   72 1510  100 1330
```

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GU  5   32  150 1230  205 1160  230 1240  271 1140  306  790  377  560  427  390
GU  5   33  429  410  436  340  462   50  483  -50  487 -150
GU  5   41870824 1140 16 -470GULL LINE D    0 2060   10 1930   72 1510  100 1300
GU  5   42  175 1120  200 1130  225 1210  270 1080  305  710  343  630  400  430
GU  5   43  414  370  434  180  457   20  482  240  490 -470
GU  5   51870930 1109 14  170GULL LINE D    0 2060   10 1930   72 1510  100 1300
GU  5   52  200 1140  225 1200  275 1050  310  680  331  630  341  630  391  460
GU  5   53  409  350  423  250  438  170
GU  5   61880119 1102 14  320GULL LINE D    0 2060   10 1940   60 1570  100 1340
GU  5   62  150 1230  200 1190  225 1250  250 1170  275 1000  300  780  325  690
GU  5   63  348  520  373  360  383  320
GU  5   71880622 1123 12  120GULL LINE D    0 2060   10 1930   60 1570  110 1230
GU  5   72  150 1230  200 1180  220 1250  270 1140  322  810  337  660  367  350
GU  5   73  397  120
GU  6   11870728 1341 11 -270GULL LINE E    0 2140   10 2040   85 1630  140 1340
GU  6   12  147 1380  193 1120  213  710  243  520  261   90  311 -170  341 -270
GU  6   21870806 1620 11 -150GULL LINE E    0 2066   10 2140  100 1560  200 1250
GU  6   22  270 1100  297  830  347  600  394  350  420  150  430   50  437 -150
GU  6   31870818 1141 14 -150GULL LINE E    0 2140   10 2140  100 1560  125 1460
GU  6   32  187 1290  225 1130  258 1190  283  940  298  820  364  570  404  360
GU  6   33  449   50  459  -60  463 -150
GU  6   41870824 1155 16 -390GULL LINE E    0 2140   10 2140  100 1560  200 1250
GU  6   42  225 1230  255 1230  297  870  340  750  340  720  358  640  380  530
GU  6   43  397  460  413  360  426  110  446 -200  459 -390
GU  6   51870930 1120 13  160GULL LINE E    0 2140   10 2140  100 1560  200 1210
GU  6   52  225 1120  262 1150  287 1030  307  860  357  650  415  410  435  280
GU  6   53  450  220  460  160
GU  6   61880119 1103 10  430GULL LINE E    0 2140   10 2140  100 1560  115 1450
GU  6   62  175 1260  200 1190  263 1180  328  760  378  560  418  430
GU  6   71880622 1142  9  120GULL LINE E    0 2140   10 2140  100 1560  135 1390
GU  6   72  185 1220  260 1140  375  620  427  260  462  120
GU  7   11870728 1405 12 -260GULL LINE F    0 2300   10 2320   85 1640  132 1430
GU  7   12  138 1440  161 1330  167 1130  188  720  213  460  229  240  279  110
GU  7   13  332 -260
GU  7   21870806 1551 15 -100GULL LINE F    0 2300   10 2300  100 1640  186 1240
GU  7   22  189 1180  200 1200  217 1150  247  920  422  680  447  610  483  510
GU  7   23  484  500  495  400  515  100  521 -100
GU  7   31870818 1202 16 -110GULL LINE F    0 2300   10 2300  100 1640  125 1470
GU  7   32  187 1290  200 1220  260 1190  290 1000  365  720  423  570  426  570
GU  7   33  438  470  444  380  469   50  475  -20  479 -110
GU  7   41870824 1205 17 -410GULL LINE F    0 2300   10 2300  100 1640  186 1240
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GU  7   42  189 1180  200 1200  255 1170  271 1140  296  940  346  780  382  680
GU  7   43  412  610  413  610  426  540  444  360  468   80  492 -410
GU  7   51870930 1140 16 -100GULL LINE F    0 2300   10 2300  100 1640  186 1240
GU  7   52  189 1180  200 1220  235 1180  244 1200  269 1160  294  960  310  920
GU  7   53  358  750  402  650  432  380  455 -190  482 -100
GU  7   61880119 1113 12  350GULL LINE F    0 2300   10 2320  110 1560  200 1210
GU  7   62  250 1190  275 1110  325  860  350  780  375  680  405  540  425  420
GU  7   63  435  350
GU  7   71880622 1136 15  190GULL LINE F    0 2300   10 2300  100 1640  186 1240
GU  7   72  189 1180  200 1220  250 1190  270 1160  295  990  345  780  389  630
GU  7   73  414  490  427  400  437  330  457  190
GU  8   11870728 1422 11  -60GULL LINE G    0 2260   10 2250   85 1700  100 1220
GU  8   12  165 1280  185 1170  210  680  235  380  252  180  302  -40  412  -60
GU  8   21870806 1558 17  -90GULL LINE G    0 2260   10 2240  100 1590  156 1210
GU  8   22  168 1260  200 1180  270 1140  300 1070  325  920  328  830  342  690
GU  8   23  384  560  400  500  417  420  497  110  525   10  530  -90
GU  8   31870818 1219 15 -110GULL LINE G    0 2260   10 2240  100 1590  156 1210
GU  8   32  160 1170  168 1260  200 1190  285 1150  325  910  330  800  390  550
GU  8   33  431  390  498   90  511  -20  515 -110
GU  8   41870824 1300 17 -320GULL LINE G    0 2260   10 2240  100 1590  156 1210
GU  8   42  168 1260  200 1180  294 1100  325  900  329  810  333  770  354  660
GU  8   43  404  500  429  420  464  280  479  170  504  -20  519 -320
GU  8   51870930 1140  9  140GULL LINE G    0 2260   10 2240  100 1590  160 1260
GU  8   52  285 1130  320  900  445  350  470  220  479  140
GU  8   61880119 1115  8  150GULL LINE G    0 2260   10 2240  100 1590  160 1260
GU  8   62  280 1130  305 1040  380  590  405  150
GU  8   71880622 1154 18  190GULL LINE G    0 2260   10 2240  100 1590  156 1210
GU  8   72  168 1260  200 1170  225 1160  244 1190  285 1140  305 1040  330  840
GU  8   73  347  770  351  700  369  620  394  500  419  400  438  300  463  190
GU  9   11870728 1458 11 -140GULL LINE H    0 2060   10 2060   90 1670  160 1200
GU  9   12  165 1270  185 1180  205  910  232  540  260  260  310   20  360 -140
GU  9   21870806 1748 14  -20GULL LINE H    0 2060   10 2070   60 1950  160 1250
GU  9   22  172 1340  272 1210  297 1270  322 1210  347  690  397  620  447  430
GU  9   23  477  300  516  100  560  -20
GU  9   31870818 1234 14 -120GULL LINE H    0 2060   10 2060   90 1950  160 1240
GU  9   32  165 1270  185 1180  200 1210  300 1180  344  640  384  560  436  380
GU  9   33  487  180  508  -20  512 -120
GU  9   41870824 1315 19 -240GULL LINE H    0 2060   10 2070   60 1950  160 1250
GU  9   42  172 1340  200 1250  258 1210  267 1200  270 1240  272 1190  297 1150
GU  9   43  312 1140  340  720  345  660  415  490  440  410  480  260  510  -40
GU  9   44  514 -240
```

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GU  9   51870930 1152 14  130GULL LINE H    0 2060   10 2070   60 1950  160 1250
GU  9   52  172 1340  200 1210  250 1180  267 1170  292 1190  318  900  338  650
GU  9   53  438  350  463  280  478  130
GU  9   61880119 1125 13  350GULL LINE H    0 2060   10 2070   60 1950  160 1250
GU  9   62  172 1340  200 1210  275 1140  300 1120  325  850  350  610  376  500
GU  9   63  401  430  426  350
GU  9   71880622 1158 13  080GULL LINE H    0 2060   10 2070   60 1950  160 1250
GU  9   72  172 1340  200 1210  275 1140  305 1100  310  950  360  590  438  290
GU  9   73  463  190  483  080
GU 10   11870729 1148 12 -230GULL LINE I    0 1450   10 1440  110 1220  160 1120
GU 10   12  185 1220  210 1010  235  730  260  430  301  170  351   10  401 -120
GU 10   13  451 -230
GU 10   21870806 1514 13  -40GULL LINE I    0 1450   10 1450  100 1250  150 1100
GU 10   22  200 1220  300 1230  320 1200  350  730  359  550  383  440  400  410
GU 10   23  461  130  473  -40
GU 10   31870818 1346 17 -370GULL LINE I    0 1450   10 1450  100 1250  150 1100
GU 10   32  200 1210  250 1160  297 1250  304 1180  319 1210  341  960  349  770
GU 10   33  367  550  400  420  417  340  445  130  464  -70  470 -370
GU 10   41870824 1330 17 -210GULL LINE I    0 1450   10 1450  100 1250  150 1100
GU 10   42  200 1220  275 1190  298 1240  305 1170  320 1200  342  920  348  770
GU 10   43  355  670  362  570  387  440  425  250  464  -10  478 -210
GU 10   51870930 1153 21 -190GULL LINE I    0 1450   10 1450  100 1250  150 1100
GU 10   52  200 1210  225 1170  250 1160  275 1210  297 1230  303 1160  309 1170
GU 10   53  316 1190  341  910  345  760  369  560  413  330  438  210  463  120
GU 10   54  488  -40  495 -140  498 -190
GU 10   61880119 1127 10  320GULL LINE I    0 1450   10 1450  100 1250  150 1100
GU 10   62  200 1220  330 1220  339 2080  384  620  399  520  419  320
GU 10   71880622 1230 20  050GULL LINE I    0 1450   10 1450  100 1250  150 1100
GU 10   72  200 1220  250 1180  295 1240  303 1190  320 1190  328 1100  338  950
GU 10   73  340  850  365  610  379  510  383  590  394  520  408  320  423  290
GU 10   74  434  270  459  050
GU 11   11870729 1220 13 -260GULL LINE J    0 1160   10 1170   85 1230  205 1230
GU 11   12  240  970  265  690  290  430  315  290  340  170  350  140  400  -10
GU 11   13  450 -130  500 -240
GU 11   21870806 1456 14  -50GULL LINE J    0 1160   10 1170  100 1220  211 1210
GU 11   22  211 1190  300 1190  360 1230  380  620  382  500  384  500  400  390
GU 11   23  435  230  446   60  452  -50
GU 11   31870818 1359 18 -200GULL LINE J    0 1160   10 1170  100 1220  200 1210
GU 11   32  211 1180  343 1240  358 1210  363  930  368  730  381  560  386  490
GU 11   33  399  390  405  370  408  380  416  310  449    0  457 -110  468 -200
GU 11   41870824 1345 16 -190GULL LINE J    0 1160   10 1170  100 1220  200 1210
```

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GU 11   42  210 1170  310 1200  345 1220  362  930  367  770  373  670  388  470
GU 11   43  398  420  405  380  416  290  447   10  466 -190
GU 11   51870930 1202  9  340GULL LINE J    0 1160   10 1170  100 1220  200 1210
GU 11   52  348 1240  371  900  372  770  386  570  410  340
GU 11   61880119 1140 11  400GULL LINE J    0 1160   10 1170  100 1220  200 1230
GU 11   62  225 1180  325 1200  347 1190  348 1010  373  650  378  590  396  400
GU 11   71880622 1227 11  060GULL LINE J    0 1160   10 1170  100 1220  200 1230
GU 11   72  210 1210  345 1240  352  945  372  670  389  290  414  120  424  060
GU 12   11870729 1344 12 -290GULL LINE K    0 1480   10 1520   70 1610  165 1380
GU 12   12  205 1360  235 1030  275  500  325  230  362   90  412  -50  462 -160
GU 12   13  517 -290
GU 12   21870806 1437 19  -10GULL LINE K    0 1480   10 1520   70 1610   95 1690
GU 12   22  150 1460  200 1350  216 1150  228 1120  229 1170  300 1220  347 1260
GU 12   23  379  590  381  670  383  510  385  480  395  340  400  310  460   90
GU 12   24  468  -10
GU 12   31870818 1411 19 -200GULL LINEK    0 1480   10 1520   80 1610   95 1690
GU 12   32  150 1460  200 1350  225 1100  229 1190  336 1210  346 1250  365  950
GU 12   33  369  740  381  550  384  490  389  470  406  300  458  100  480 -100
GU 12   34  492 -200
GU 12   41870824 1355 17 -140GULL LINE K    0 1480   10 1520   80 1610   95 1690
GU 12   42  150 1460  200 1350  229 1190  279 1220  348 1260  361 1070  369  760
GU 12   43  372  690  379  560  384  520  404  340  463   60  482 -140
GU 12   51870930 1209 20 -160GULL LINE K    0 1480   10 1520   70 1610   95 1690
GU 12   52  150 1460  200 1350  216 1150  229 1170  230 1170  280 1190  305 1190
GU 12   53  324 1230  340  940  341  770  352  570  384  310  409  160  434   30
GU 12   54  459 -130  462 -160
GU 12   61880119 1200 11  540GULL LINE K    0 1480   10 1520   70 1610   95 1690
GU 12   62  150 1460  200 1350  216 1150  229 1190  310 1210  315  870  335  800
GU 12   71880622 1241 16  140GULL LINE K    0 1480   10 1520   70 1610   95 1690
GU 12   72  150 1460  200 1350  216 1150  279 1220  304 1200  320 1030  338  750
GU 12   73  344  660  369  470  385  360  410  200  419  140
GU 13   11870729 1404 16 -300GULL LINE L    0 1790   10 1820   77 1970  127 1680
GU 13   12  197 1360  211 1360  226 1180  239 1120  242  930  262  600  278  450
GU 13   13  323  250  363  100  413  -60  463 -190  524 -300
GU 13   21870808 1403 13    0GULL LINE L    0 1790   10 1830   77 1980  200 1360
GU 13   22  230 1230  300 1190  354 1200  384  650  398  580  400  550  406  480
GU 13   23  460  100  466    0
GU 13   31870818 1422 16 -200GULL LINE L    0 1790   10 1830   77 1980  200 1360
GU 13   32  230 1230  330 1200  347 1240  354 1200  359 1070  375  790  399  560
GU 13   33  403  500  433  290  470    0  479 -100  506 -200
GU 13   41870824 1405 16 -150GULL LINE L    0 1790   10 1830   77 1980  200 1360
```

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GU 13   42  230 1230  249 1230  254 1180  280 1200  359 1160  374  800  384  690
GU 13   43  396  540  401  510  418  360  462   50  489 -150
GU 13   51870930 1212 13 -160GULL LINE L    0 1790   10 1830   77 1980  200 1360
GU 13   52  230 1230  315 1180  357 1190  373  900  397  590  406  330  430  120
GU 13   53  459 -130  462 -160
GU 13   61880119 1152 12  430GULL LINE L    0 1790   10 1830   75 1980  200 1360
GU 13   62  230 1240  330 1210  352 1190  354 1140  355  990  370  770  382  610
GU 13   63  399  430
GU 13   71880622 1241 13 -006GULL LINE L    0 1790   10 1830   75 1980  200 1360
GU 13   72  230 1240  330 1210  350 1210  357 1020  384  640  392  530  434  254
GU 13   73  454  144  474 -006
GU 14   11870729 1427 15 -240GULL LINE H    0 2120   10 2120   30 2140  130 1600
GU 14   12  200 1300  213 1320  227 1220  230  940  236  810  261  490  326  220
GU 14   13  351  130  401   10  451 -130  515 -240
GU 14   21870808 1244 14 -260GULL LINE H    0 2120   10 2130   30 2150  100 1770
GU 14   22  200 1310  214 1330  300 1240  340 1250  378  580  400  500  424  420
GU 14   23  468  220  474   50  488 -260
GU 14   31870818 1440 16 -200GULL LINE H    0 2120   10 2130   30 2150  100 1770
GU 14   32  200 1310  216 1330  241 1210  331 1230  343 1240  360  960  368  770
GU 14   33  389  560  424  420  453  280  489    0  505 -200
GU 14   41870824 1420 14  -80GULL LINE H    0 2120   10 2130   30 2150  100 1770
GU 14   42  200 1310  300 1230  342 1250  367  790  378  670  387  600  414  490
GU 14   43  433  390  478  120  501  -80
GU 14   51870930 1230 16 -150GULL LINE H    0 2120   10 2130   30 2150  100 1770
GU 14   52  200 1310  213 1330  238 1220  263 1180  288 1180  313 1220  345 1200
GU 14   53  366  810  444  300  469  110  494  -50  508 -150
GU 14   61880119 1204 12  490GULL LINE H    0 2120   10 2130   30 2150  100 1770
GU 14   62  200 1300  225 1270  300 1230  350 1150  354 1060  379  740  386  550
GU 14   63  406  490
GU 14   71880622 1304 21  010GULL LINE H    0 2120   10 2130   30 2150  100 1770
GU 14   72  200 1310  225 1290  275 1180  300 1210  347 1210  355 1040  364  910
GU 14   73  380  740  388  650  394  600  397  600  400  530  419  440  444  320
GU 14   74  458  240  483  110  498  010
GU 15   11870729 1445 14 -200GULL LINE N    0 2170   10 2190   35 2220  135 1600
GU 15   12  195 1290  201 1320  209  860  225  610  243  460  293  290  330  180
GU 15   13  380   50  430  -50  483 -200
GU 15   21870808 1216 14 -120GULL LINE N    0 2170   10 2270   30 2240  100 1810
GU 15   22  190 1310  200 1300  331 1250  344 1190  368  790  400  660  460  370
GU 15   23  500  170  510  -20  520 -120
GU 15   31870818 1506 15 -240GULL LINE N    0 2170   10 2270   30 2240  100 1810
GU 15   32  190 1310  200 1300  275 1180  340 1200  375  720  429  550  432  510
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GU 15   33  452  410  482  250  520  -40  535 -240
GU 15   41870824 1430 13  -80GULL LINE N    0 2170   10 2270   30 2240  100 1810
GU 15   42  190 1310  200 1300  300 1190  340 1190  370  760  395  660  457  430
GU 15   43  504  120  522  -80
GU 15   51870930 1230 15  120GULL LINE N    0 2170   10 2270   30 2240  100 1810
GU 15   52  190 1310  200 1300  275 1180  300 1170  350 1210  371  920  383  790
GU 15   53  453  480  482  330  507  180  517  120
GU 15   61880119 1212 14  490GULL LINE N    0 2170   10 2190   30 2230  100 1810
GU 15   62  190 1310  200 1310  250 1180  300 1190  340 1190  347 1040  372  780
GU 15   63  383  690  408  540  418  490
GU 15   71880622 1301 15  030GULL LINE N    0 2170   10 2190   30 2230  100 1810
GU 15   72  190 1310  200 1300  300 1170  325 1200  332 1210  342 1010  352  620
GU 15   73  360  530  438  230  463  120  483  030
GU 16   11870808 1135 15 -260GULL LINE O    0 1590   10 1560  100 1370  144 1240
GU 16   12  165 1299  200 1140  250 1130  290 1120  400  660  450  450  496  180
GU 16   13  504    0  508  -40  513 -160  515 -260
GU 16   31870818 1516 14 -320GULL LINE O    0 1590   10 1560  100 1370  144 1240
GU 16   32  165 1299  265 1120  365  780  456  490  459  440  468  380  475  340
GU 16   33  487  180  513 -120  519 -320
GU 16   41870824 1440 14 -120GULL LINE O    0 1590   10 1560  100 1370  144 1240
GU 16   42  165 1299  200 1140  250 1130  290 1090  365  770  412  590  437  530
GU 16   43  464  350  495   80  510 -120
GU 16   51870930 1238 15 -340GULL LINE O    0 1590   10 1560  100 1370  144 1240
GU 16   52  165 1299  175 1180  250 1140  285 1110  360  810  373  750  443  500
GU 16   53  471  250  496   20  515 -210  518 -340
GU 16   61880119 1221 15  450GULL LINE O    0 1590   10 1570  100 1370  144 1240
GU 16   62  165 1300  200 1140  215 1120  265 1110  290 1090  315  980  340  860
GU 16   63  365  740  388  630  413  490  423  450
GU 16   71880622 1313 22 -040GULL LINE O    0 1590   10 1570  100 1370  144 1240
GU 16   72  165 1300  190 1170  240 1130  286 1110  336  890  351  820  353  790
GU 16   73  357  700  366  570  366  570  372  480  397  370  412  330  418  314
GU 16   74  432  274  460  170  485  020  501 -040
```

APPENDIX B

SEDIMENTARY FEATURES

This appendix presents sedimentologic features observed along the shorelines of the lower Columbia River. Common terminology used in shore studies are listed below.

DEFINITION OF SHORE TERMINOLOGY
(Komar, 1986; King, 1972; USACE, 1984)

Shore: the strip of ground bordering any body of water whether the ground is rock or loose sediment. If it is unconsolidated sediment, then shore becomes synonymous with beach used in its restricted sense.

Offshore zone: (Bagnold, 1963) area extending from bed contour at which depth admits disturbance of bed sediment by wave motion inward to the contour at which waves begin to break.

Shoreline: the line of demarcation between the water and the exposed beach.

Backshore: portion of profile extending landward from the sloping foreshore to the point of development of vegetation or change in physiography.

Beach face: sloping section of the beach profile below the berm which is normally exposed to the action of wave swash.

Beach scarp: vertical escarpment notch into beach profile by wave erosion, height is commonly less than a meter, but can be higher.

Berm: nearly horizontal portion of the beach or backshore formed by the disposition of sediment by receding waves - some beaches may have more than one.

Breaker zone: portion of the nearshore region at which the waves arriving from offshore reach instability and break. With very simple uniform waves, such as those generated in a wave tank, the zone may be reduced to a breaker line.

Foreshore: sloping portion of the beach profile lying between a berm crest (or in the absence of

a berm crest, the upper limit of wave swash at high tide) and the low-water mark of the backrush of the wave swash at low tide.

Surf zone: the portion of the nearshore region in which bore-like translation waves occur following wave breaking - the dissipation of wave energy by surface turbulence. This portion extends from the inner breakers shoreward to the swash zone.

Swash zone: portion of the nearshore region in which the beach face is alternately covered by the uprush of the wave swash and exposed by the backwash, the zone of residual wave motion.

STRATIGRAPHIC SECTIONS

Set No. 1 Profile PU11, 29JUL88
Alluvial or "micro-bajada" laminae

laminae thickness (mm)

10
5
10
5
4
3 laminae
3 inclined 49° to shore
6
12
7
17
3
3
15

STATISTICS

mean	=	7.15 mm
median	=	5.0 mm
std. dev.	=	4.83
range	=	14
min.	=	3 mm
max.	=	17 mm

Data recorded from trench in profile PU11, 29JUL88.
SET No. 2
Wave laminae

laminae thickness (mm)	
5	
6	
3	
5	
4	
8	
5	
10	laminae
3	inclined 9° to shore
8	
3	
6	
5	
5	
8	
3	
5	
3	
7	
2	
8	
4	
4	
4	
15	
2	
3	laminae
7	inclined 5° to shore
3	
7	
4	
13	
4	
6	
3	
7	
5	
3	
10	

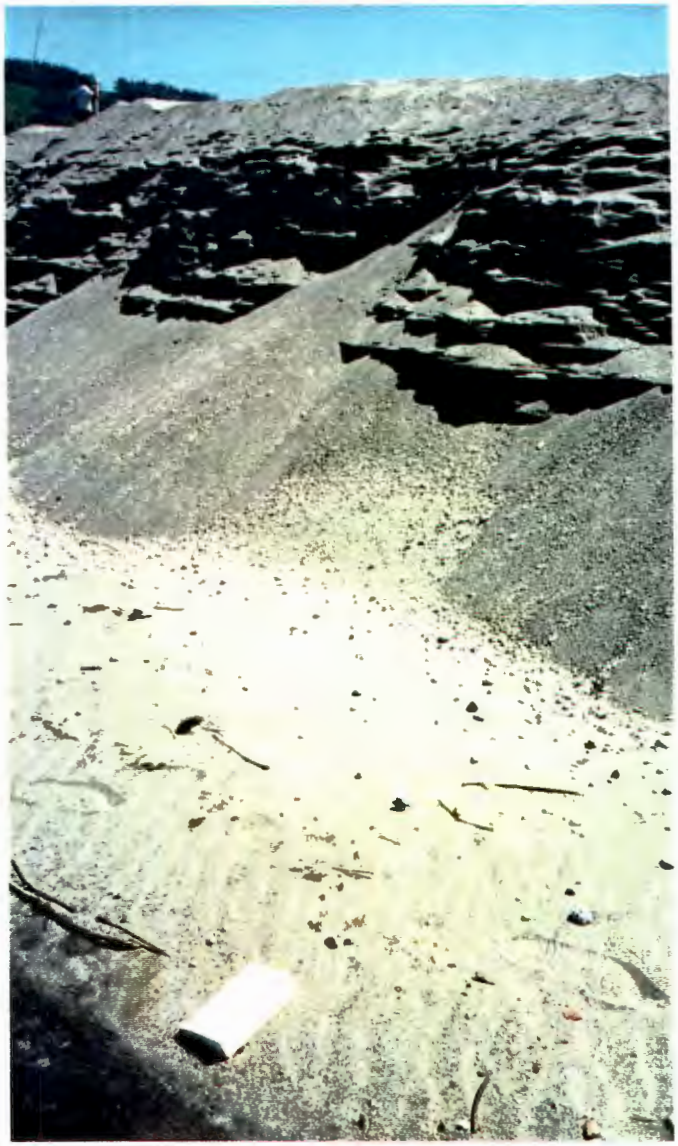
laminae thickness (mm)	
4	
3	
6	
2	
10	laminae
5	inclined 5° to shore
4	
6	
2	
5	
6	
6	
3	
3	
12	
7	
3	
6	
4	
4	
7	
3	
5	
3	
2	
12	
5	
3	
10	
5	
10	
5	

STATISTICS
mean = 5.46 mm
median= 5.0 mm
std. dev.= 2.85
Range =13 mm
min. = 2 mm
max. = 15 mm

The following photos exhibit shore morphology and sedimentary structures moving from supratidal zone (above highest high water) to water depths of about 50 cm.

Eolian features observed on sandy shore slopes above highest high water in the study region. Dune size decreases shoreward from the crest of the beach scarp.

Eolian dune. Note coarse grained dune crest and finer grained troughs, clearly apparent in grain size distributions. Predominant wind direction is right to left, blowing from the west.



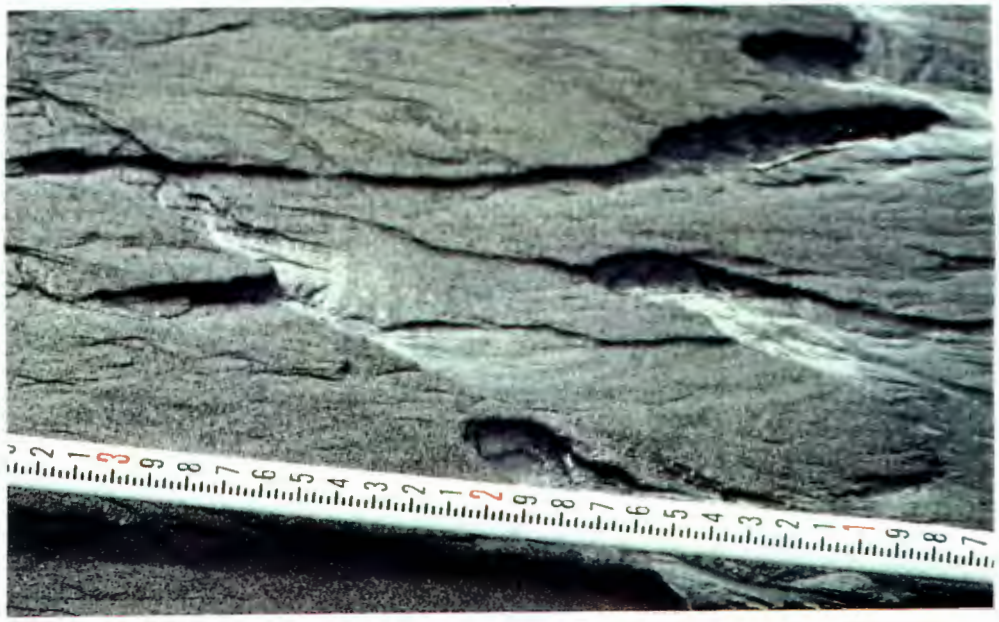
Beach scarp in sand disposal pile. Note distinct fan development and terraces developed by wind erosion. Note accumulation of pumice and dacite cobbles on upper beach along with eolian ripples. High water is marked by the heavy mineral band in the lower left. Wallace Island site, June 24, 1988.

High water wave swash up to base of beach scarp at Wallace Island site. June 24, 1988.

Beach scarp that lies completely above high water, as interpreted by lack of swashed features, beach scarp and the occurrance of distinct eolian dunes down to the heavy mineral band in the extreme left. Surface bedforms suggest dominant wind direction is to the east, as at Price and Puget Islands.

Active beach scarp at Wallace Island site. Note eolian dunes above scarp and heavy mineral band with lobate swash pattern below, two distinct sedimentary environments.

Beach scarp exposing cross-bedding of eolian dunes.

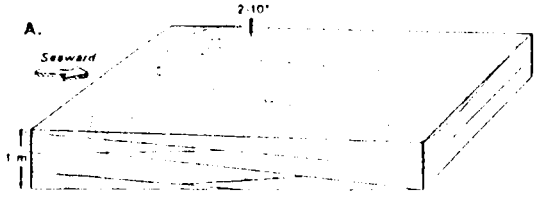


Runnels at Puget Island site, occurring in site shore notch (profiles 3-9). Runnels form from the discharge of groundwater out of the beach. Groundwater is recharged at high water. Seepage out of the beach face is at a much lower rate than the tidally driven drop in the river's water level.

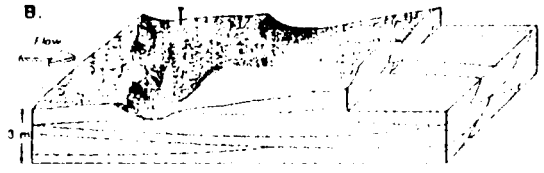
Micro-dendrentic drainage patterns form cutting into the beach and moving sand down the beach face. Beach runnels occur below highest high water. The groundwater table lowers slower than the tide and releases water onto steeper slopes at lower tides, leading to runnels.

Distinct zone of heavy mineral accumulation on surface of beach face, associated with the high water line. Heavy minerals make up approximately 5-10 percent of the Columbia River sand.

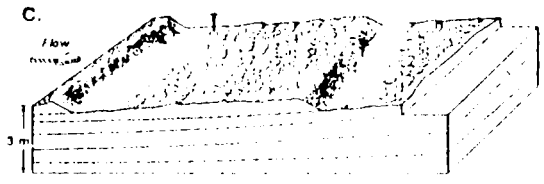
Mineral separation patterns on beach face. Profile no.10, Puget Island site, June 13, 1988.



SWASH CROSS STRATIFICATION. Low-angle (2°-10°) cross stratification, subparallel to bases of wedge-shaped sets. Stratification and set boundaries are formed parallel to changing slope of beachface and dip generally seaward.

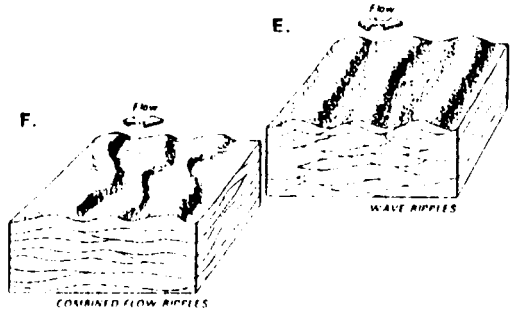


LARGE-SCALE TROUGH CROSS STRATIFICATION formed by subaqueous dunes or "megaripples". High-angle (25°-30°) cross stratification, tangential to bases of trough-shaped sets. Cross strata dip parallel to flow direction.



TABULAR CROSS STRATIFICATION FORMED BY MIGRATING SAND WAVES. High-angle (near 30°) cross stratification in tabular sets. Cross strata are planar and angular to bases of sets where flow is steady but may be tangential under some conditions.

HUMMOCKY CROSS STRATIFICATION. Low-angle (less than 15°) cross stratification, subparallel to smooth, undulatory lower boundaries of sets. Similar appearance in all vertical orientations. Commonly associated with wave ripples.

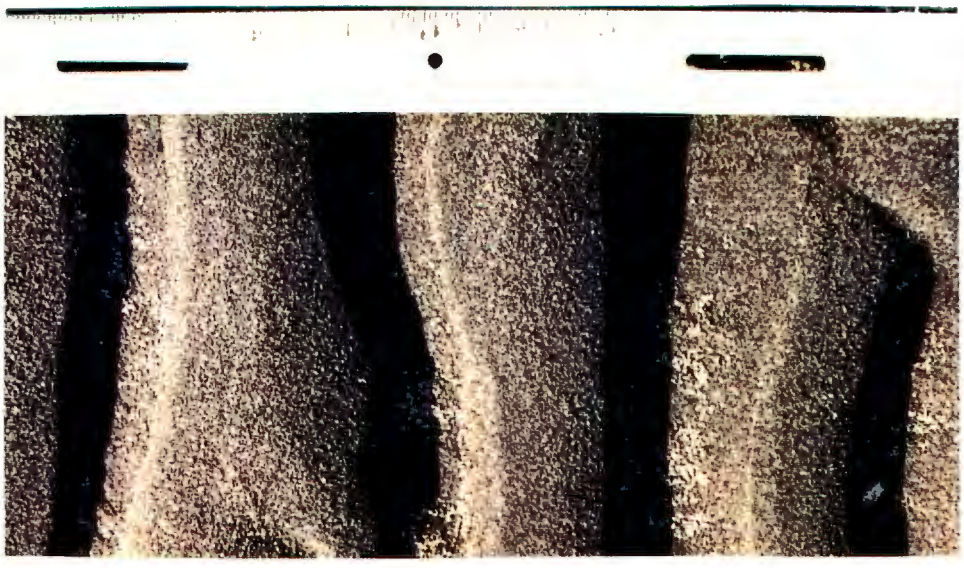


WAVE RIPPLES. Ripple-trough profiles are symmetrical and rounded, and stratification dips in both directions of oscillatory flow.

COMBINED-FLOW RIPPLES. Formed by superimposed wave and current action or by shoaling waves. Small-scale cross strata are curved and tangential, dipping in direction of dominant flow.

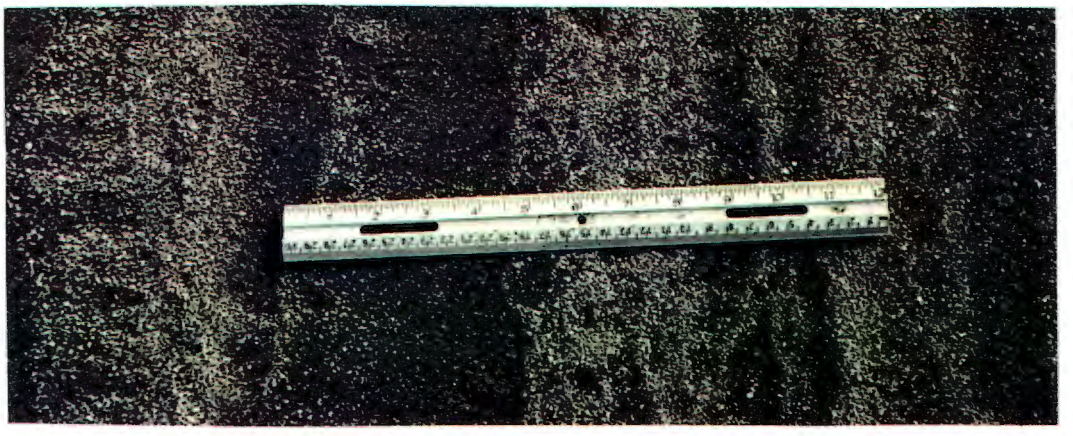
Common stratification types and associated bedforms in coastal-marine sands. Variations in form related to grain size, changing flow conditions, and rates of deposition (In: Scholle and Spearing, 1982, p.249). The study region shows excellent examples of the stratification patterns displayed in D, E, and F.

Looking down at preserved wind wave generated ripples on the beach face of Puget Island site profile no.11, September 16, 1987. Note bifurcating and symmetrical pattern characteristic of a wave dominated sedimentary environment.



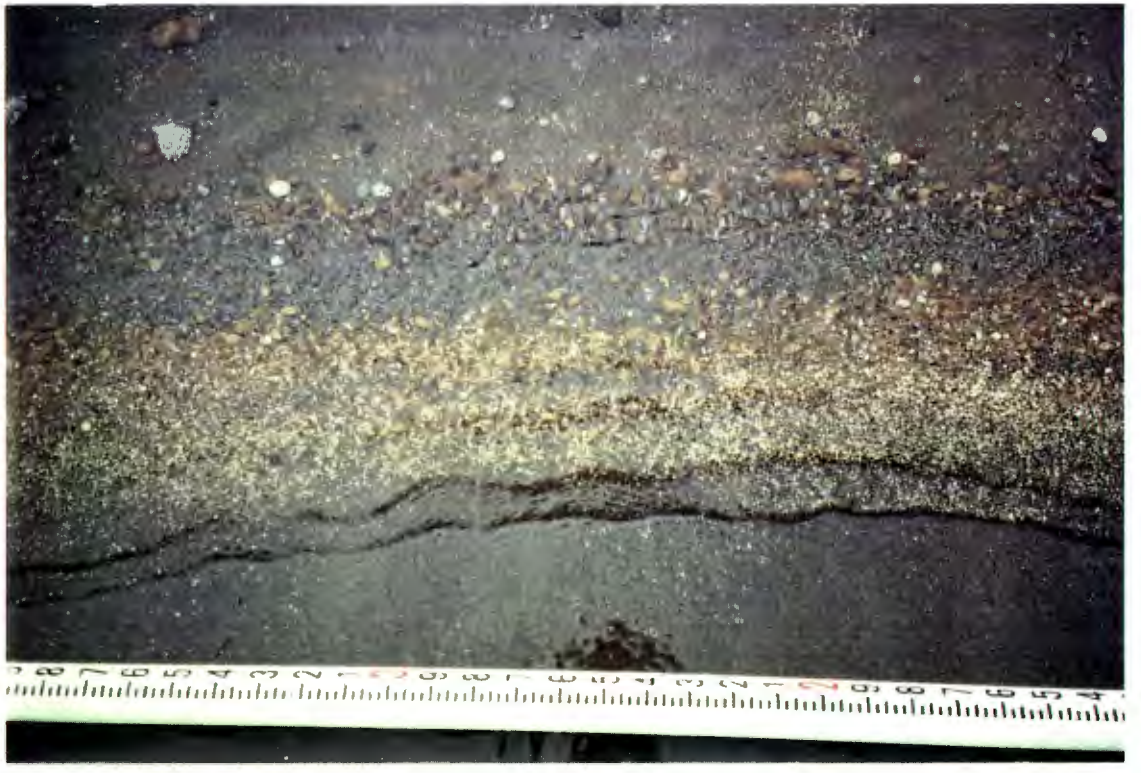
Close-up of same ripples. Note flattening of ripple crests that occurs by swash action at the water's edge as the water level drops across the beach face. Pumice grains accumulate in the troughs.

Puget Island site beach face along profile no.11, 16SEP87. Waterline lies to the right of the photograph. This photo illustrates some interesting bedform development. The debris line visible in the upper left marks highest high water swash from run-up caused by a ship wave. The pumice swash delineates mean highest high water. No ripples are preserved in the upper beach, but as the rate of water level retreat increases during a drop in the tide, ripples become more completely preserved. Note that the most susceptible portion of the ripples are destroyed, their crests.

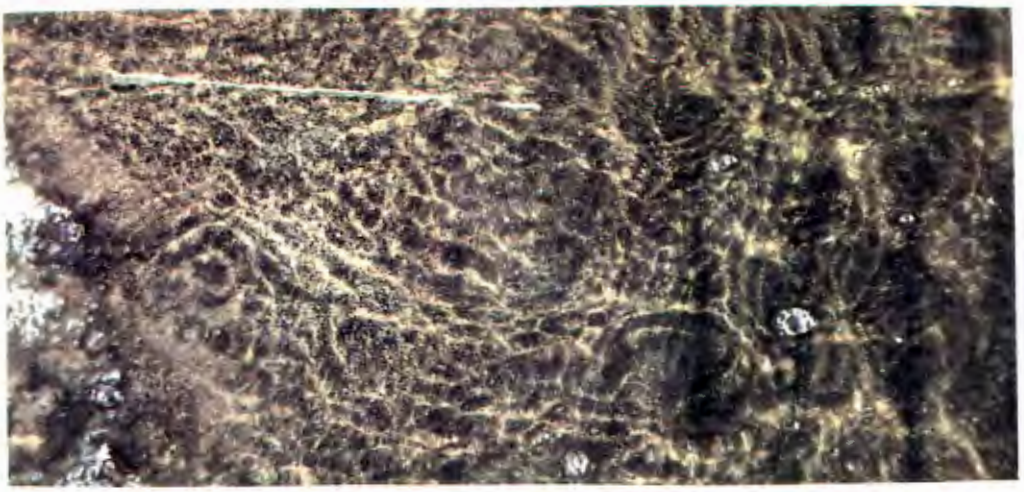


Close-up of same site exhibiting the pumice swash bands. Note the pumice grains are larger than the mean grain size. This size difference and the lower density of pumice grains makes the pumice very susceptible to entrainment and transport.

Conditions at the water's edge along beach face. Note lobate swash patterns delineated by pumice grains. The low density of the pumice and the larger size relative to the mean grain size of the sediment population, results in the pumice being easily moved. Thus the pumice ends up at the hydraulic boundary in which energy is delivered; the shoreline.



Active berm at the water's edge. Note distinct difference in grain size shoreward and riverward of this berm. This characteristic of the structures. The berm edge, slightly riverward of the water's edge was used as the water surface point in the level and rod surveying. Vista Park beach, Skamokawa, Washington, RK 54, 26AUG87.



Looking down at beach face just below the water's edge, which lies just to the left of the field of view. Note wind oscillatory wave ripples to the right. Edge of berm is marked by change between ripples to planar bed just left of center. Ruler is 1 foot (30.5cm) in length. Puget Island site, profile no.11, 16JUN87.

Looking down at beach face just above the water's edge, located at extreme right. Note the smooth, planar bed that is characteristic of the swash zone, especially the swash zone at tidal extremes where the water remains in one position for a longer period. Ripple preservation is apparently dependent upon the rate of water level regression down beach face. Puget Island site, profile no.11, 16JUN87.

APPENDIX C

SHIP WAVES

This appendix includes the data recorded by the low pressure transducer of ship waves at the Puget Island site. Information is also listed describing the ships, date and time, and tidal elevation.

Merchant Vessels[1,2]

Ship	Type	Date/time	draft	length	beam	displ.
El Garen outbound	cargo	09/15/87	9.51	216.4	32.3	24,760
Ocean Beauty inbound	bulk	09/15/87 15:17	7.00	175.3 (BB)	23.4	16,636
Valdiva outbound	bulk	09/15/87 16:00	12.00	224.9 (BB)	32.3	61,161
Chevron Oregon inbound	tanker	09/17/87 12:54	10.67	198.1	29.3	37,602
Magnolia inbound	bulk	09/17/87 15:25	7.01	196.0 (BB)	29.6	30,127
Cordiality inbound	bulk	09/17/87 16:03	4.00	197.8 (BB)	24.3	12,548
Evelyn Maersk inbound	tanker	09/18/87	11.00	182.6 (BB)	32.2	45,636
Hyundai #108 inbound	car	09/18/87	7.20	173.7 (BB)	27.7	8,809
Kee Lung inbound	bulk	09/18/87 15:35	6.50	187.4 (BB)	28.3	22,612
Luna II inbound	bulk	10/29/87 13:30	9.54	182.8 (BB)	28.5	33,381
Lake River inbound	bulk	10/29/87 14:00	7.49	225.8 (BB)	32.3	38,815
Leonadros inbound	bulk	10/30/87 13:30	7.80	220.0 (BB)	32.3	34,446
European Hwy inbound	car	06/08/88 11:15	7.01	180.0	32.2	12,437
Coast Range inbound	tanker	06/09/88 13:00	7.32	220.7 (BB)	31.0	27,685

Merchant Vessels[1,2]

Ship	Type	Date/time	draft	length	beam	displ.
Ocean Jade	bulk	06/13/88	8.30	192.0	30.0	28,950
inbound		13:10		(BB)		
Verranzano Br.	cont.	06/13/88	6.13	264.5	32.3	18,176
inbound		11:33		(BB)		
outbound		06/14/88	10.67	264.5	32.3	31,638
		16:40				
Indah Fuji	bulk	06/14/88	6.72	160.0	25.0	16,714
inbound		12:30		(BB)		

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[1] Dimensions from Lloyd's Register, 1988-89.
[2] Drafts from Columbia River Pilots, 1988.
[3] Dimensions from Janes Fighting Ships, 1987-88.

cont. = container ship
Br. = Bridge
Hwy = Highway

1988 Rose Festival Naval Vessels[3]

Ship	Type	Date/time	draft	length	beam	displ.
USN Chandler outbound	naval destroyer	06/14/88 16:00	6.20 ("Kidd" class)	171.6	16.8	6,210
USN Ford inbound	naval frigate	06/09/88 09:07	4.50 ("Oliver Hazard Perry" class)	135.6	13.7	2,750
USN Thach outbound	naval frigate	06/09/88 11:35	4.50 ("Oliver Hazard Perry" class)	135.6	13.7	2,750
USN Gray inbound outbound	naval frigate	06/09/88	7.80 ("Knox" class)	133.5	14.3	3,011
USN Kansas City inbound	naval oiler	06/08/88	10.20 (no wave record)	200.9	29.3	13,000
USN Mt. Vernon inbound	naval	06/08/88 11:30	6.00 dock landing ship	168.6	25.6	8,600
USN Ramsey inbound	naval frigate	06/09/88 09:45	4.60 ("Brooke" class)	126.3	13.5	2,640
USCG Boutwell outbound	cutter	06/13/88 13:45	6.10 ("Hamilton" and "Hero" class)	115.2	13.1	3,050
USCG Iris outbound	tender bouytender	06/13/88 13:52	4.00 "Balsam" class	54.9	11.3	935

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[1] Dimensions from Lloyd's Register, 1988-89.
[2] Drafts from Columbia River Pilots, 1988.
[3] Dimensions from Janes Fighting Ships, 1987-88.

cont. = container ship
Br. = Bridge
Hwy = Highway

Merchant Vessels[1,2]

Ship	Velocity m/s	Velocity knots	Bc	Bf	DD (cm)	H_{max} (cm)	T_{max} (sec)	DD (s)	d (cm)
El Garen outbound	8.7	16.8	0.37		-	-	-		
Ocean Beauty inbound	7.5	14.6	0.58	.022	36.3	27.0	4.10	26	119
Valdiva outbound	5.2	10.1	-		5.0	7.0	2.20	-	180
Chevron Oregon inbound	5.9	11.6	0.607	.041	34.0	17.1	2.14	37	96
Magnolia inbound	6.1	12.0	0.745	.028	23.6	38.1	3.74	55	150
Cordiality inbound	5.1	9.9	0.656	.013	4.0	17.1	2.43	-	122
Evelyn Maersk inbound	-	-							40
Hyundai #108 inbound	6.4	12.5	-	-	-	-			
Kee Lung inbound	7.1	13.9	0.651		33.0	15.0	3.76	30	122
Luna II inbound	5.9	11.5	0.673	.037	57.2	30.5	3.76		79
Lake River inbound	6.7	13.1	0.033	.033	26.5	16.0	4.14	40	79
Leonadros inbound	5.6	10.9	0.035	.035	26.7	15.2	3.38	-	104
European Hwy inbound	7.4	14.3	0.		38.0	30.0	4.80	35	113
Coast Range inbound	6.9	13.5	0.555	.029	25.0	11.0	4.50	30	155
Ocean Jade inbound	5.8	11.3	0.606	.033	15.2	27.8	3.76	40	110
Verranzano Br. inbound	6.0	11.9	0.35	.033	53.3	19.0	3.76	35	95
outbound	7.2	13.0	0.35	.045	157.0	61.0	4.60		
(outbound record lost)									
Indah Fuji inbound	6.6	12.9	0.622	.023	35.0	19.0	3.76	40	143

[1] Dimensions from Lloyd's Register, 1988-89.
[2] Drafts from Columbia River Pilots, 1988.
[3] Dimensions from Janes Fighting Ships, 1987-88.

cont. = container ship
Br. = Bridge
Hwy = Highway

1988 Rose Fesitval Naval Vessels[3]

Ship	Velocity m/s	Velocity knots	Bc	Bf	DD (cm)	H_{max} (cm)	T_{max} (sec)	d (cm)
USN Chandler								
outbound		13.8			22.9	20.9	3.76	143
USN Ford								
inbound		16.7			3.8	41.9	4.60	146
USN Thach								
outbound	7.2	14.0	0.429	.009	0.0	8.0	3.00	116
USN Gray								
inbound	8.1	15.7			8.0	43.0	4.50	198
outbound	6.6	11.9	0.478	.009	15.2	36.2	4.51	119
USN Mt. Vernon								
inbound		13.6			21.0	22.9	4.50	125
USN Ramsey								
inbound	7.8	15.2			0.0	38.1	4.50	168
USCG Boutwell								
outbound	8.1	15.7	0.331	.010	0.0	33.5	4.50	137
USCG Iris								
outbound	5.7	11.1	0.413	.006	0.0	22.9	3.76	137

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[1] Dimensions from Lloyd's Register, 1988-89.
[2] Drafts from Columbia River Pilots, 1988.
[3] Dimensions from Janes Fighting Ships, 1987-88.

cont. = container ship
Br. = Bridge
Hwy = Highway

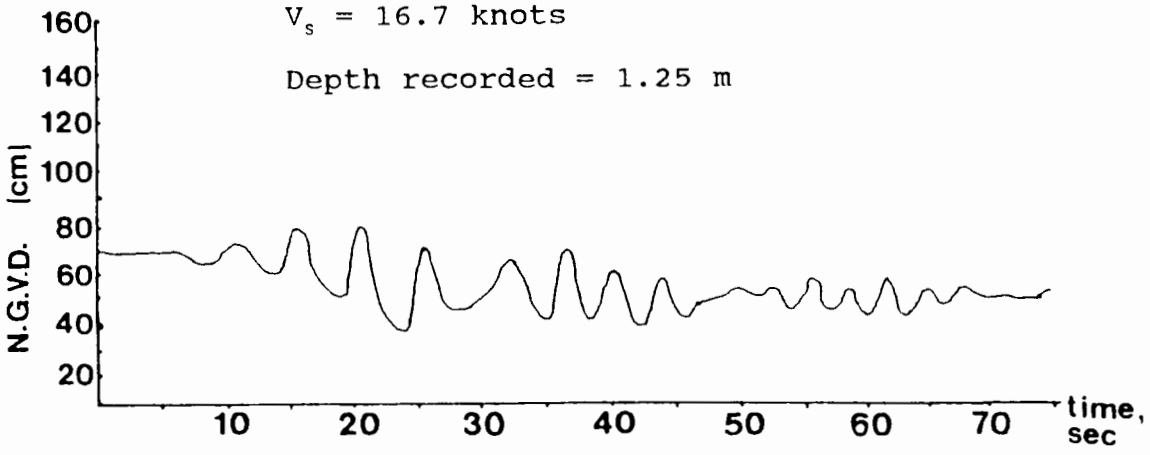
Maximum Design Draft and Deadweight Tonnage

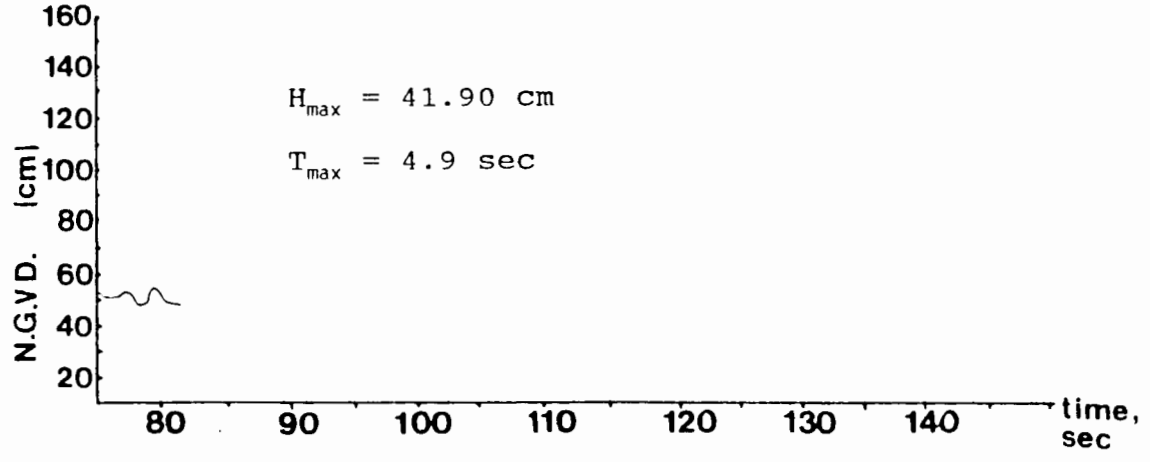
From Lloyd's (1988) Listing of Ship Parameters

Ship	Maximum Draft (m)	Deadweight (tonnes)
El Garen	10.82	28,173
Ocean Beauty	10.41	24,740
Valdiva	12.92	65,785
Chevron Oregon	11.31	39,847
Magnolia	9.06	38,918
Cordiality	11.17	35,110
Evelyn Maersk	12.20	50,600
Hyundai #108	7.99	9,783
Kee Lung	10.75	37,389
Luna II	10.83	37,895
Lake River	13.20	68,407
Leandros	12.35	54,540
European Highway	8.20	14,569
Coast Range	10.74	40,631
Ocean Jade	10.67	37,217
Verranzano Bridge	12.04	35,582
Indah Fuji	10.00	24,872

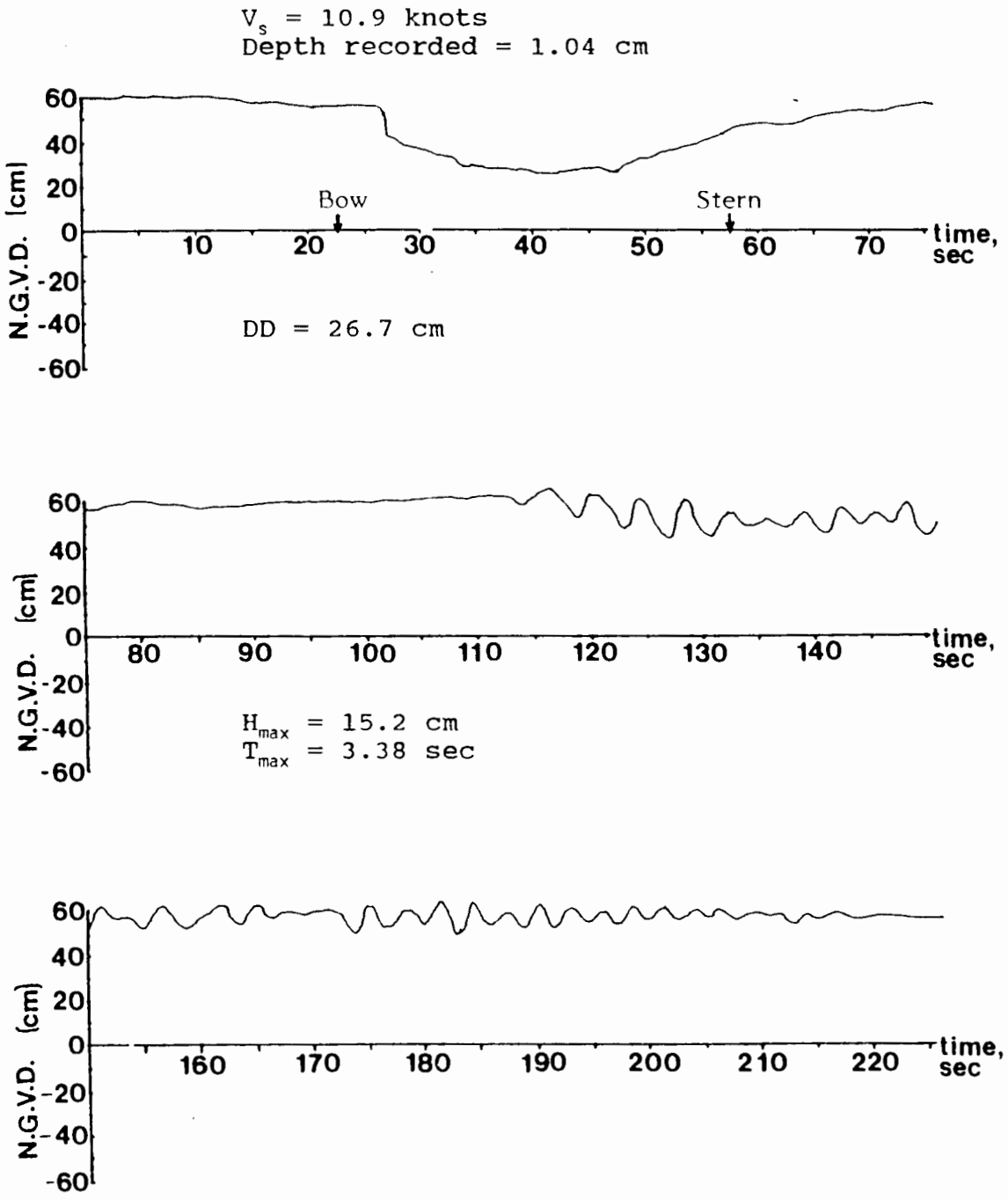
From Jane's Fighting Ships 1987-1988

	draft (m)	standard displ. (tonnes)
USN Chandler (996)	6.20	3,050
USN Ford (54)	4.50	2,750
USN Thach (43)	4.50	2,750
USN Gray (1054)	4.60	3,011
USN Kansas City (32)	10.20	12,500
USN Mt. Vernon (39)	6.00	8,600
USN Ramsey (2)	4.60	2,640
USCG Boutwell	6.10	3,050
USCG Iris	4.00	935

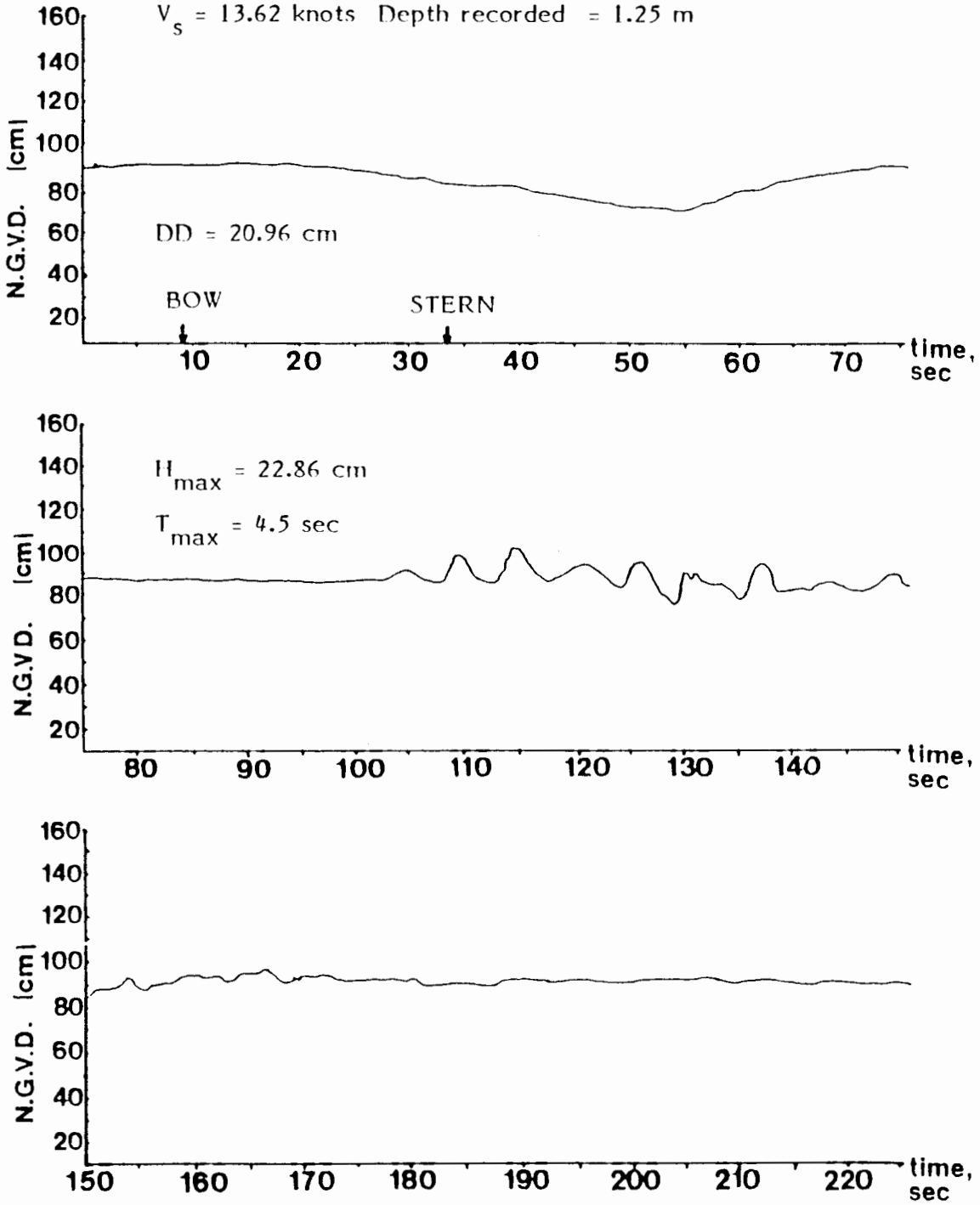




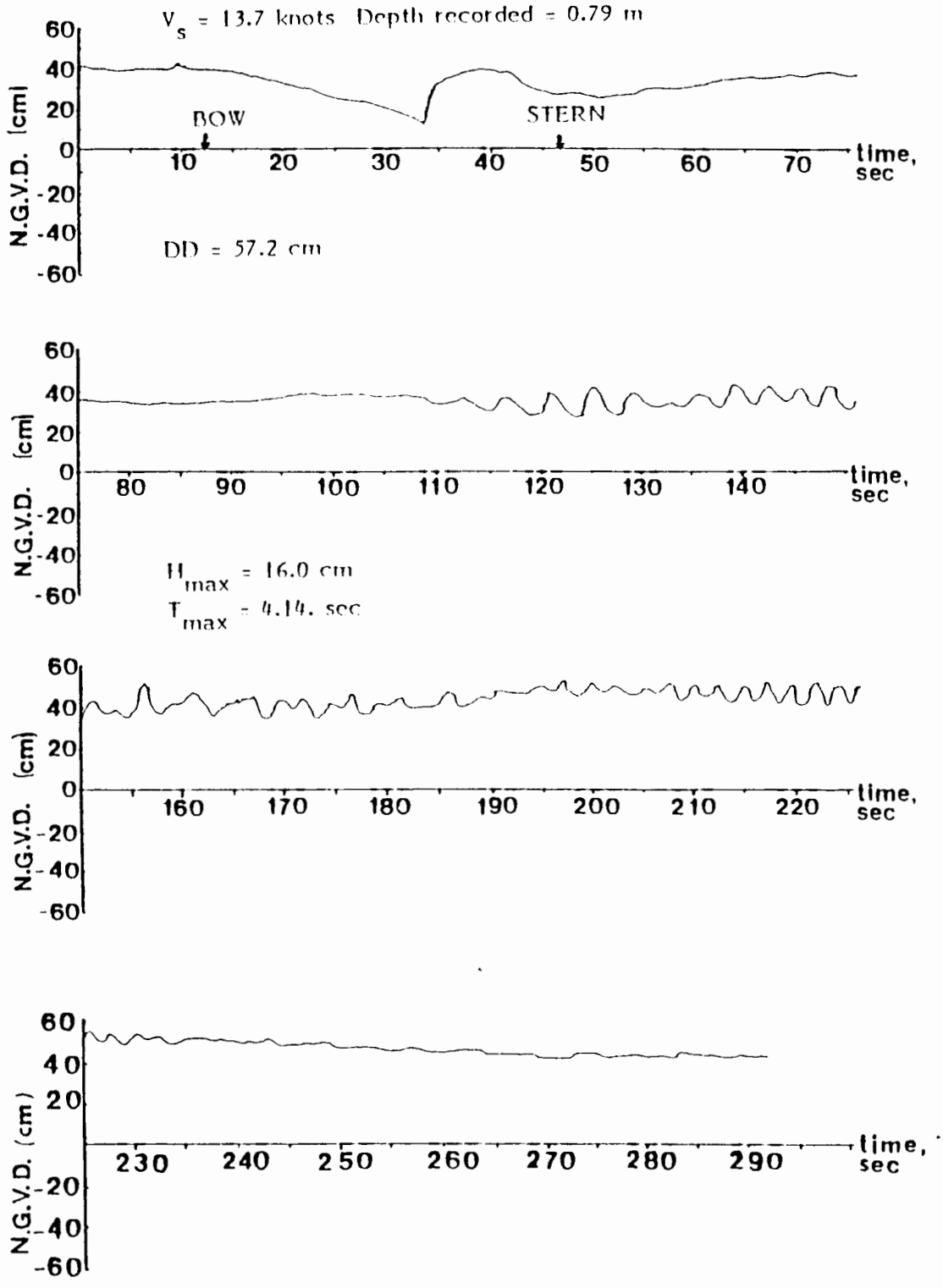
Ship wave record, Puget Island, WA RK 62
USN Ford 09JUN88 09:07 UPSTREAM



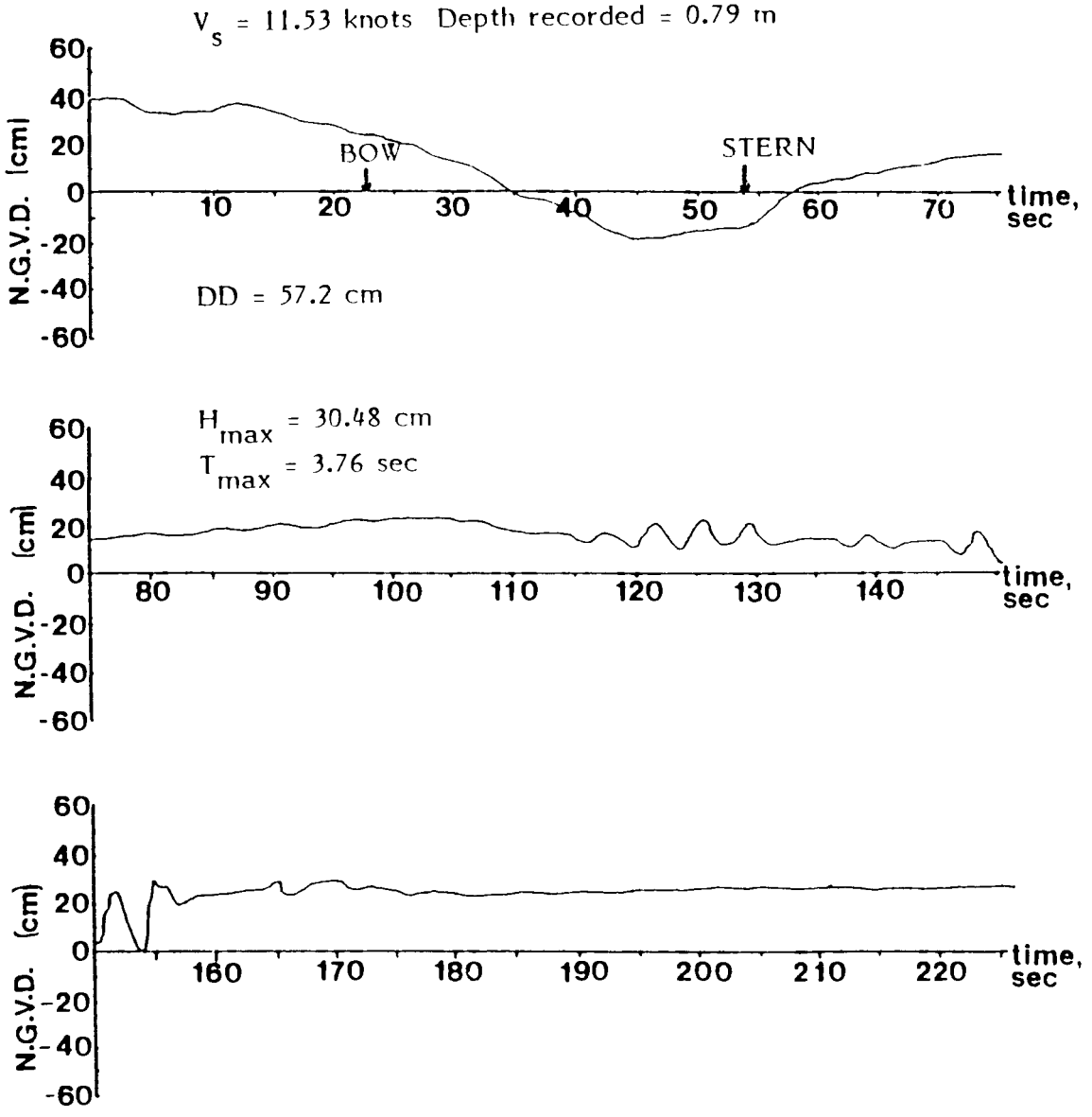
Ship wave record, Puget Island, WA RK 62
Leonadros 30OCT87 UPSTREAM 13:30



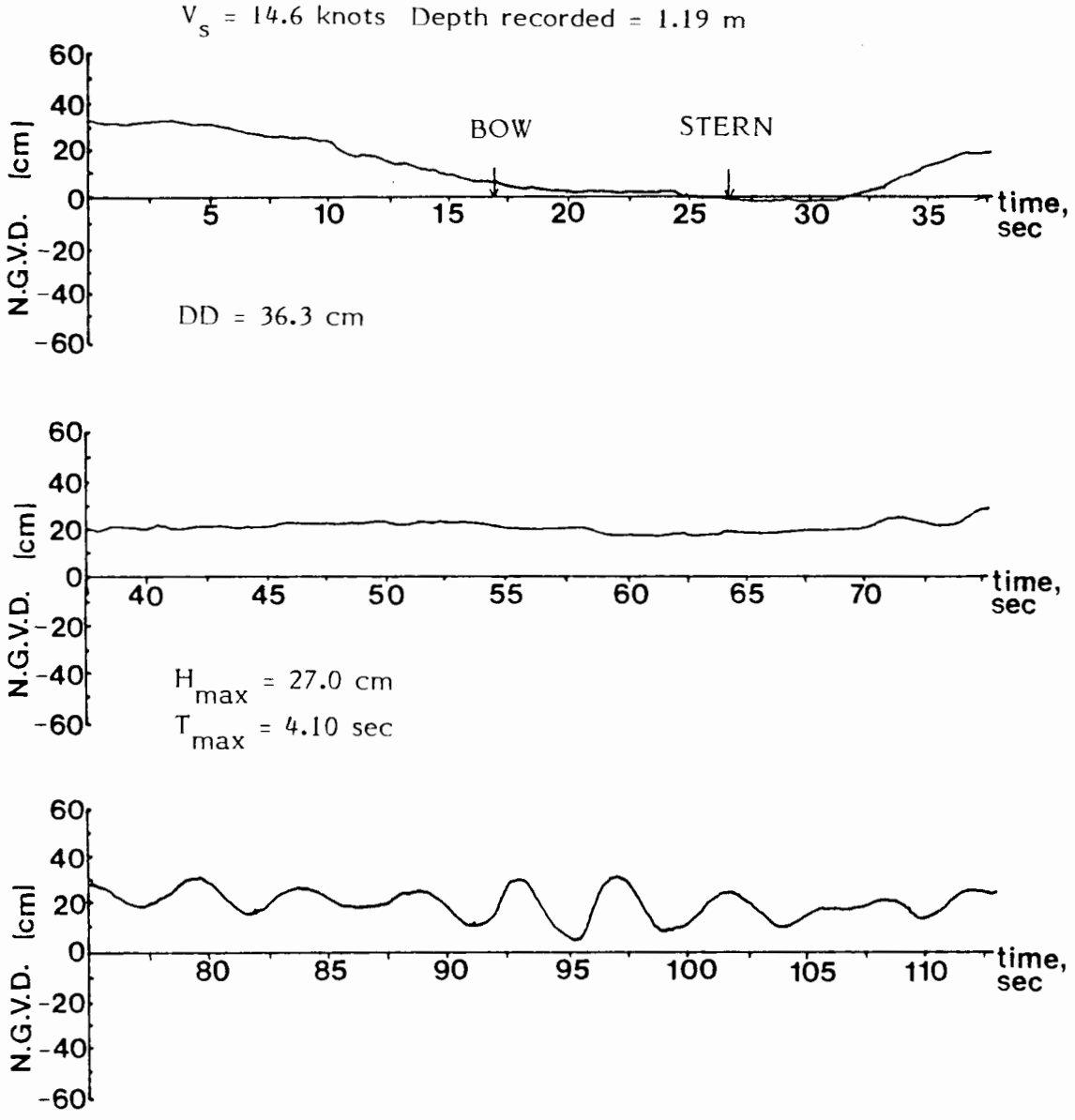
Ship wave record, Puget Island, WA RK 62
USN Mt. Vernon (#39) 08JUN88 UPSTREAM 11:30



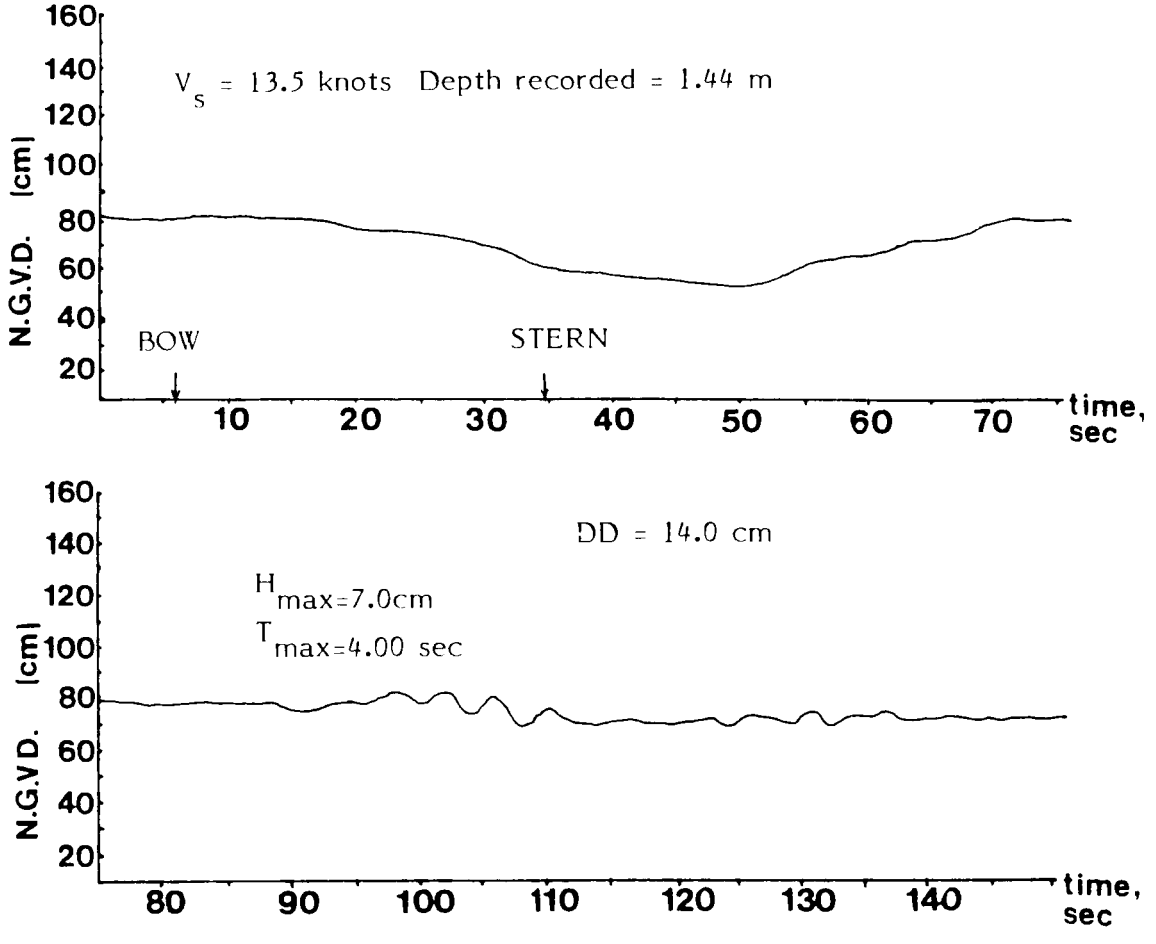
Ship wave record, Puget Island, WA RK 62
Lake River 29OCT87 UPSTREAM 14:00



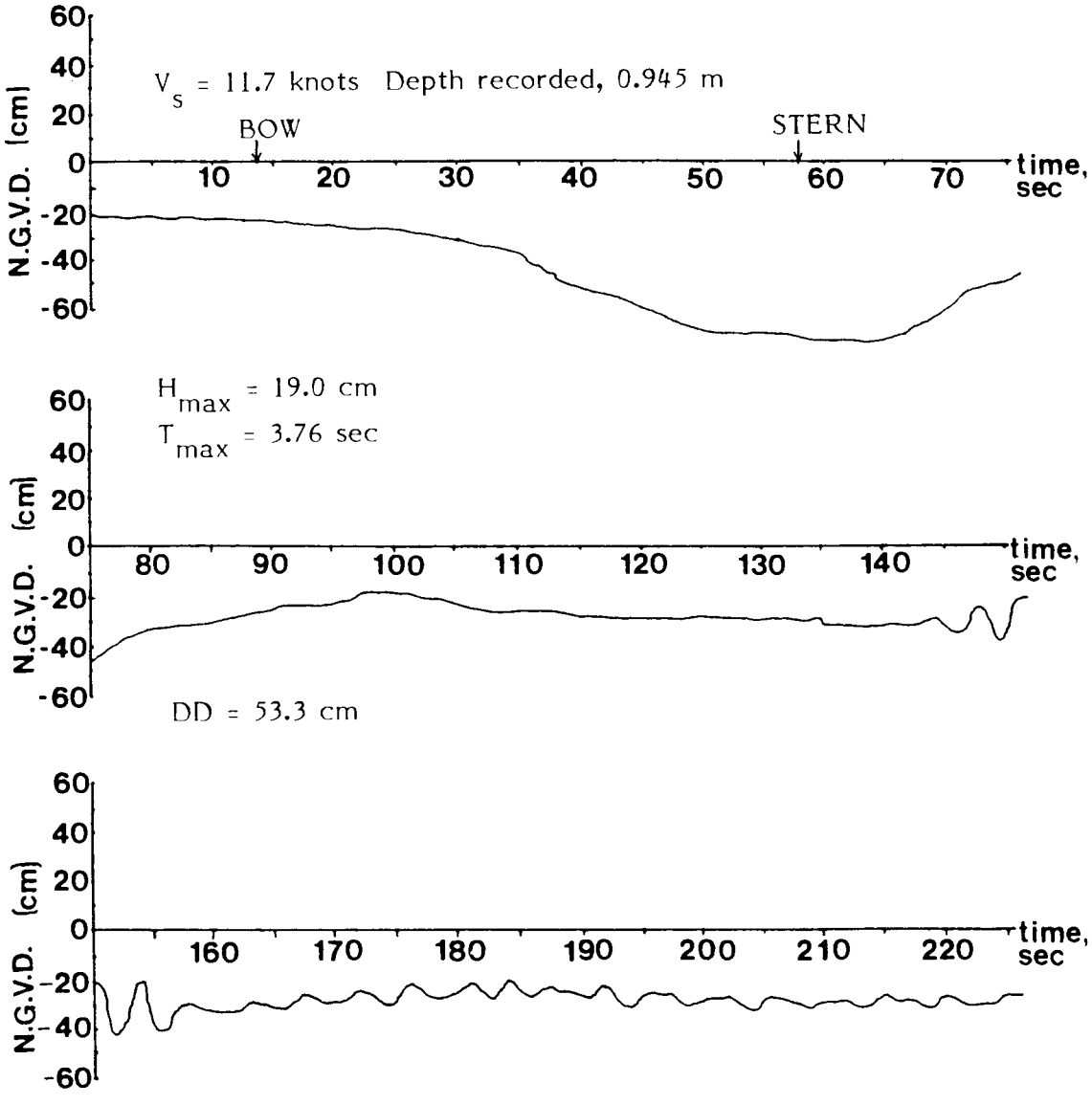
Ship wave record, Puget Island, WA RK 62
Luna II 29OCT87 UPSTREAM 13:30



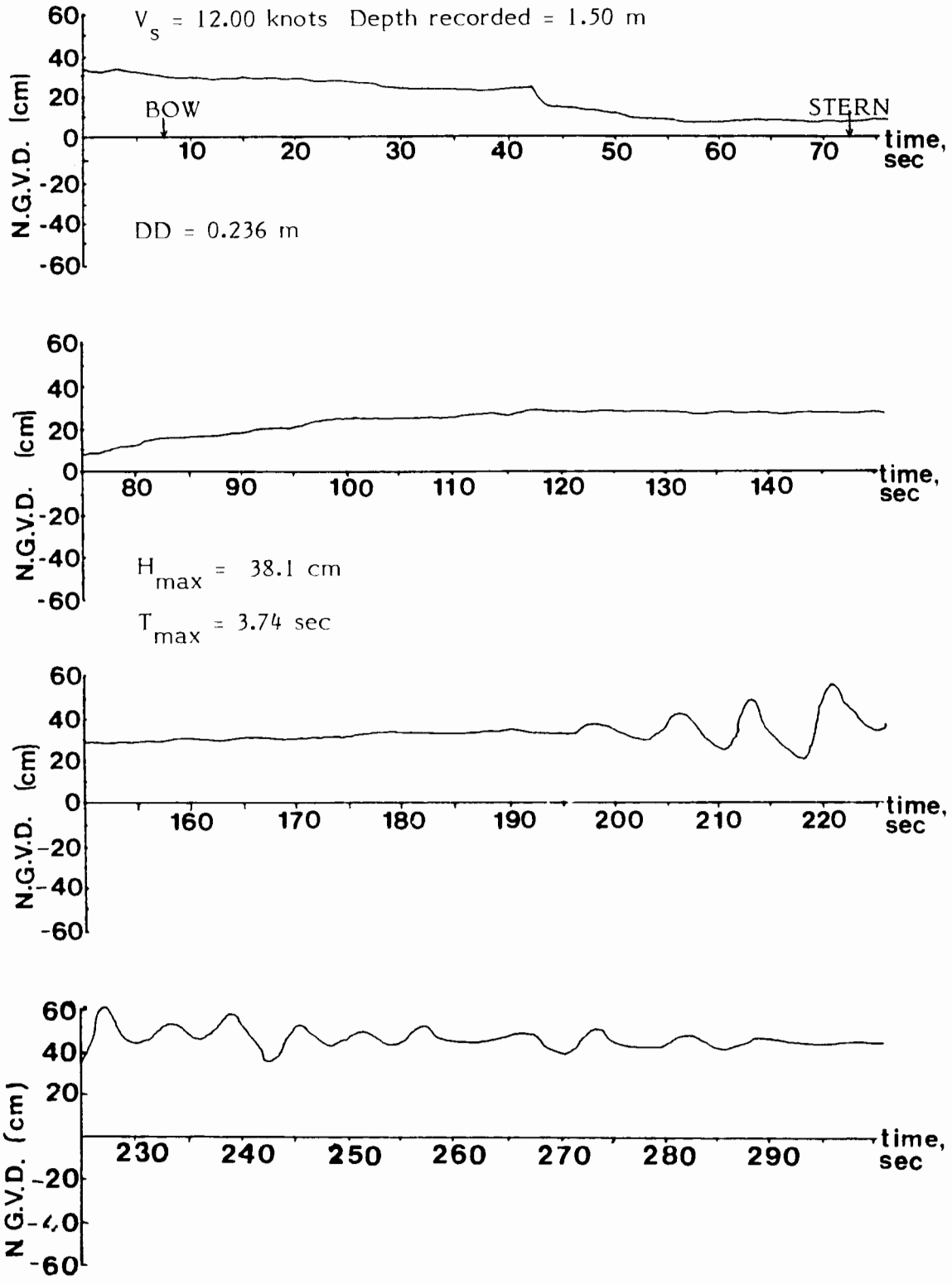
Ship wave record, Puget Island, WA RK 62
Ocean Beauty 15SEP87 UPSTREAM 15:17



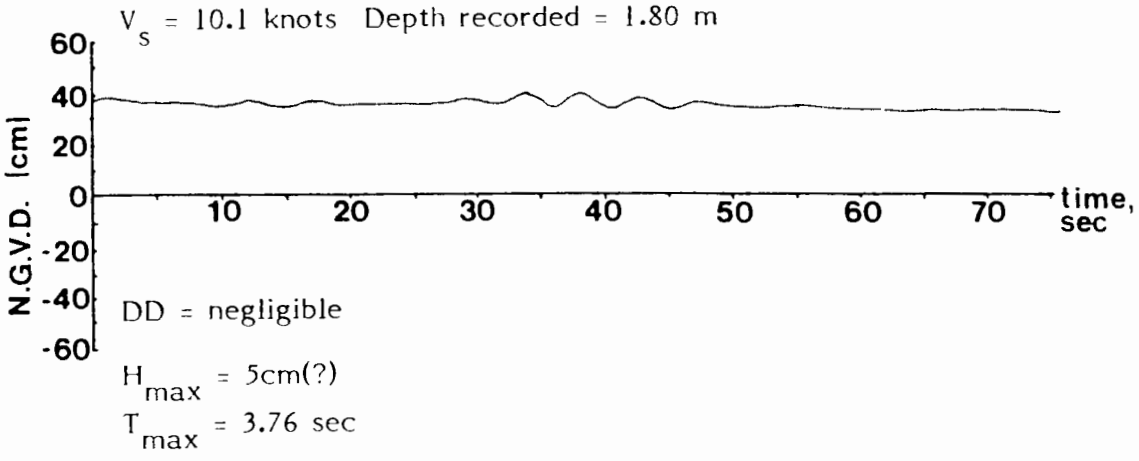
Ship wave record, Puget Island, WA RK 62
Coast Range 098JUN88 UPSTREAM 13:00



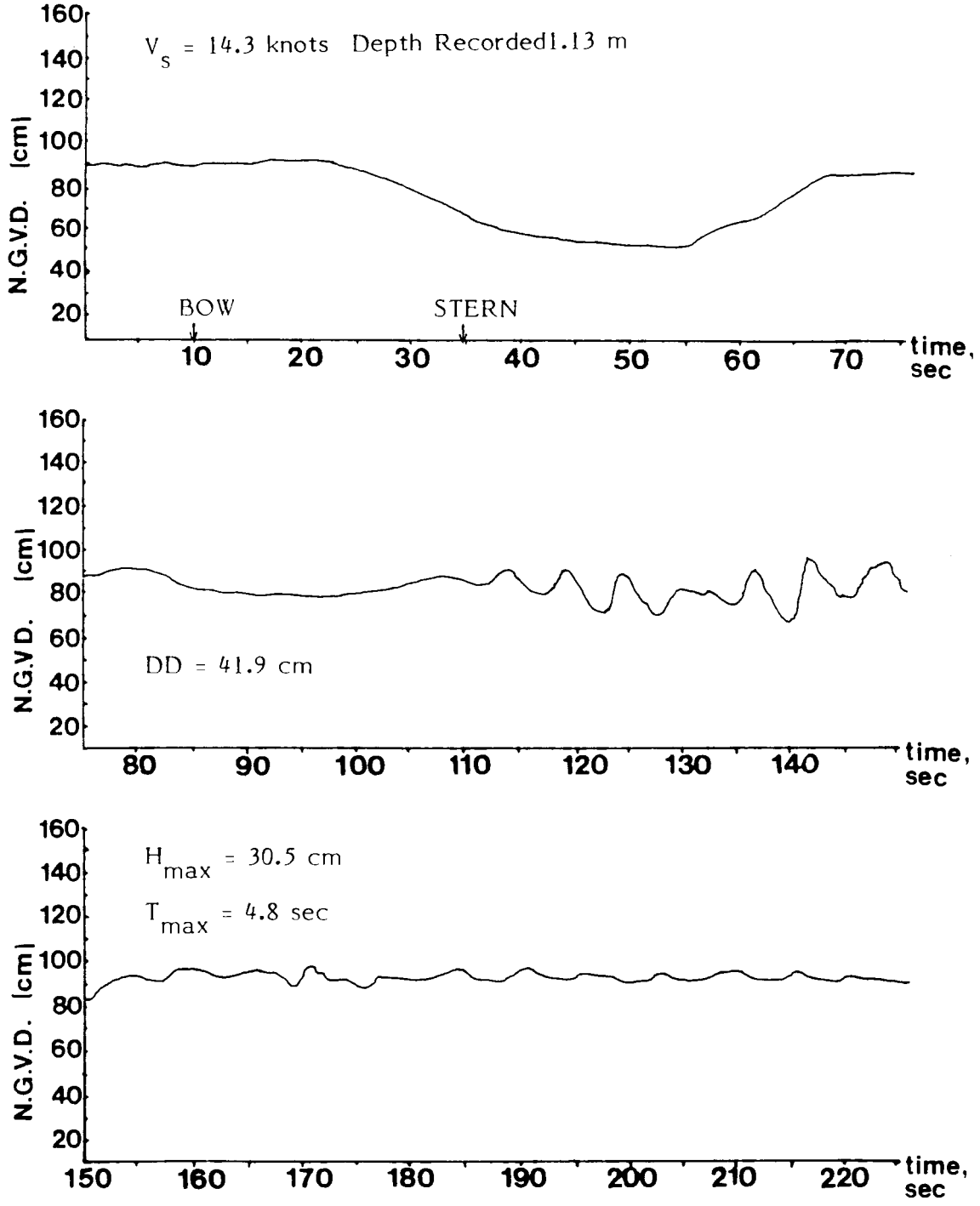
Ship wave record, Puget Island, WA RK 62
Verranzano Bridge 13JUN88 UPSTREAM 11:33



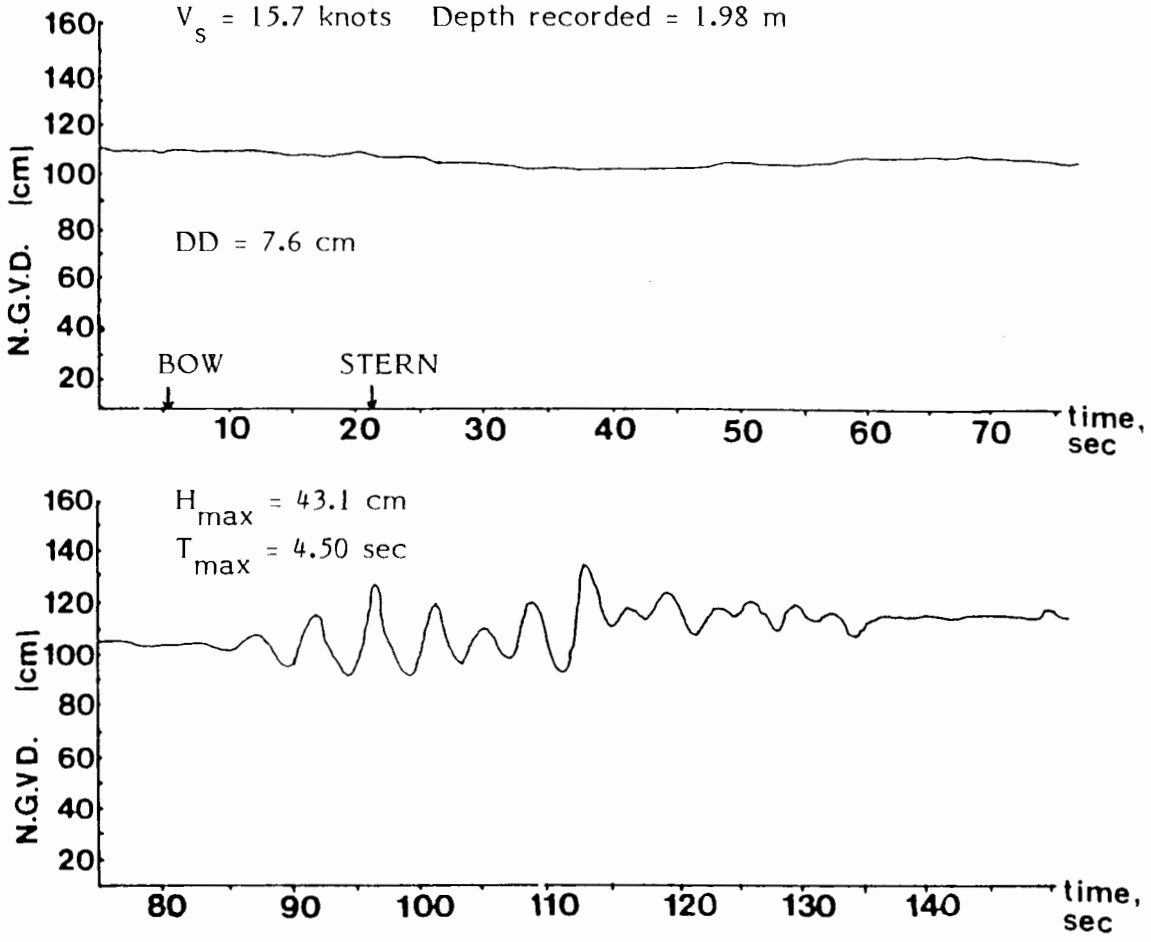
Ship wave record, Puget Island, WA RK 62
Magnolia 17SEPT87 15:25



Ship wave record, Puget Island, WA RK 62
Valdiva 15SEPT87 DOWNSTREAM 16:00

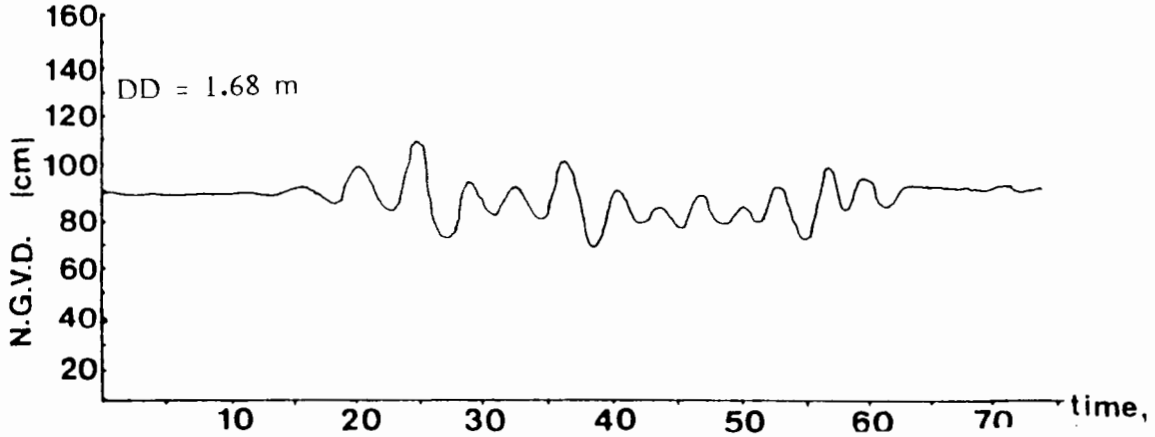


Ship wave record, Puget Island, WA RK 62
European Highway 08JUN88 UPSTREAM 11:15



Ship wave record, Puget Island, WA RK 62
USN Gray 09JUN88 UPSTREAM 10:23

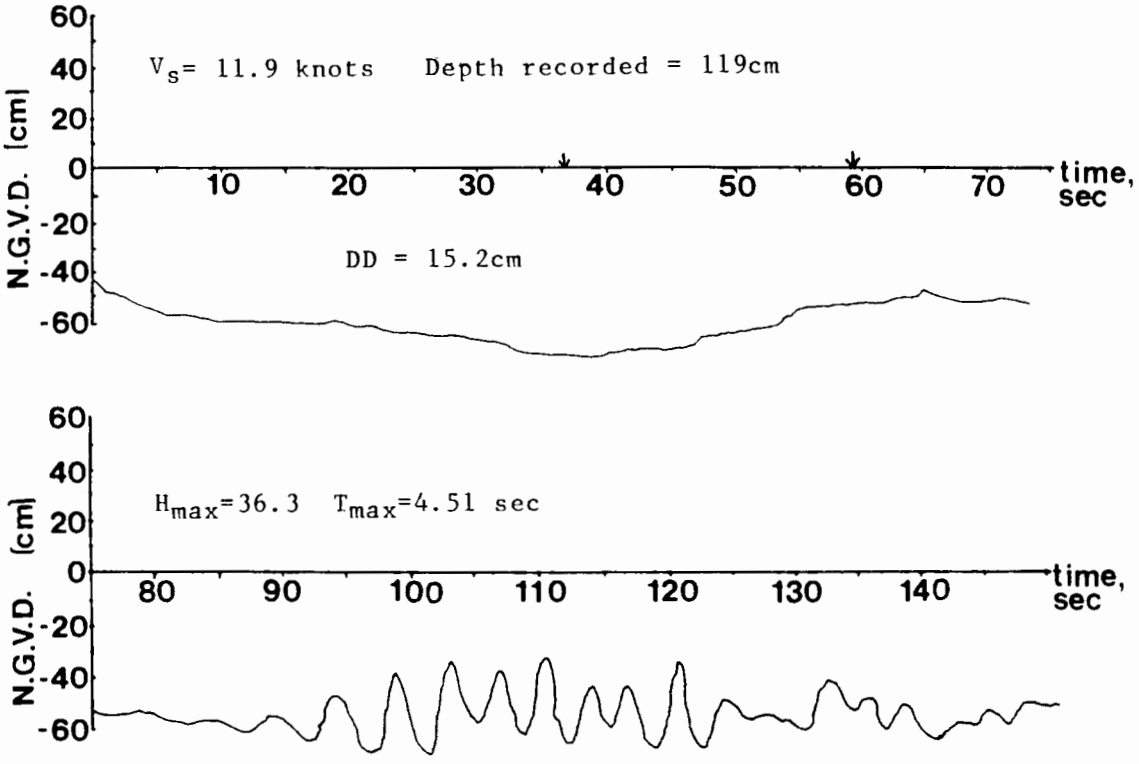
V_s = 15 knots Depth recorded 1.68 m



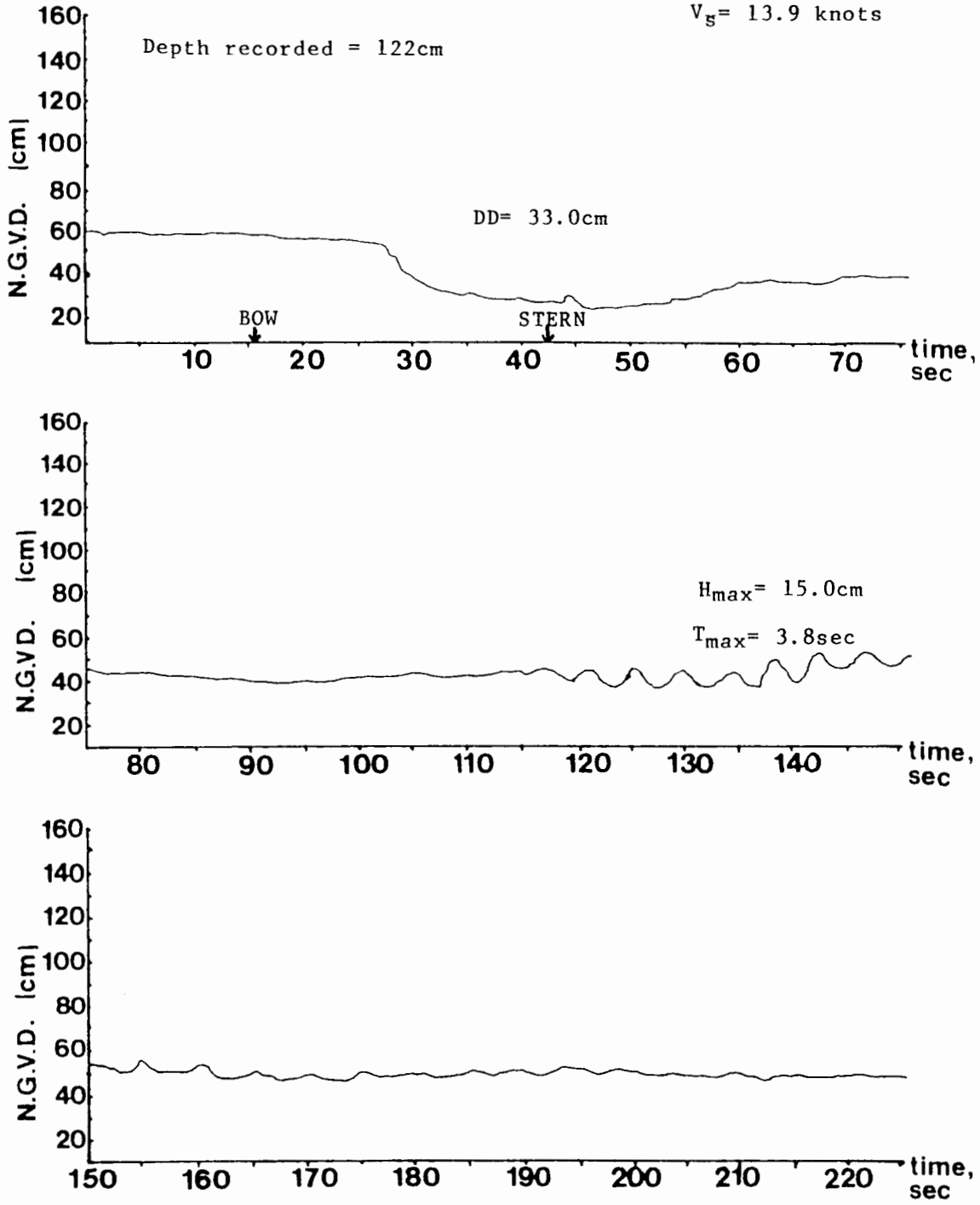
H_{max} = 38.1 cm

T_{max} = 4.5 sec

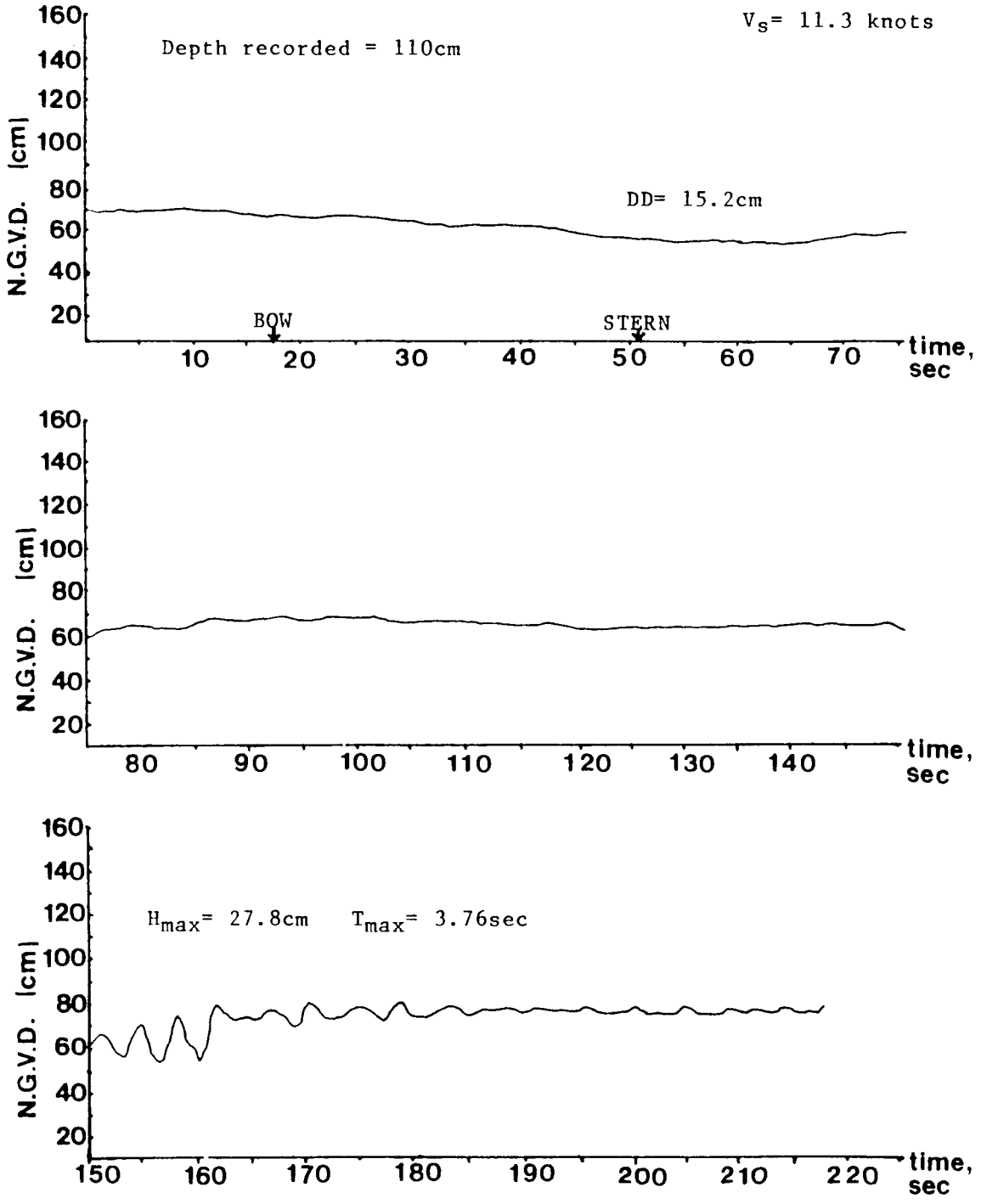
Ship wave record, Puget Island, WA RK 62
USN Ramsey 09JUN88 UPSTREAM 9:45



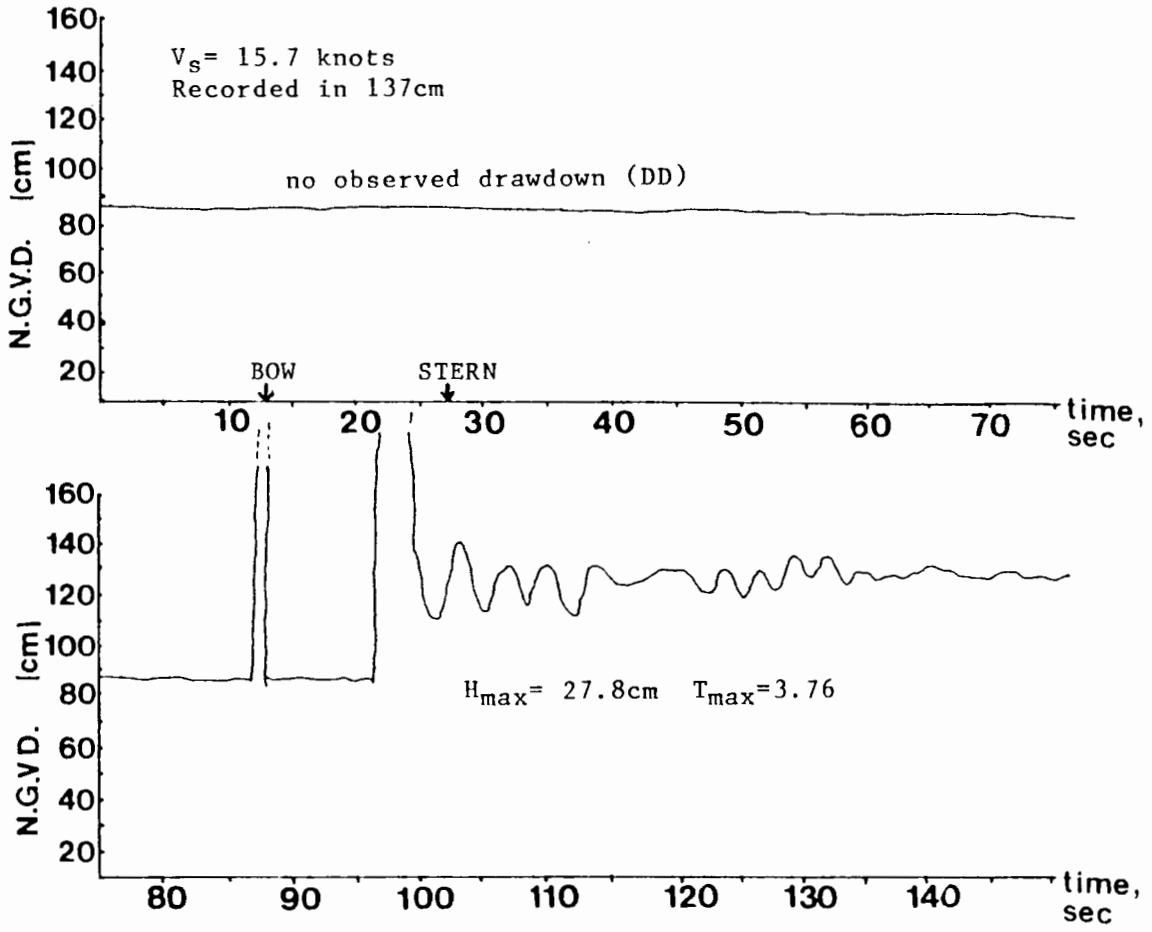
Ship wave record, Puget Island, WA RK 62
USN "Gray" (1054) 14JUN88 DOWNSTREAM 08:52



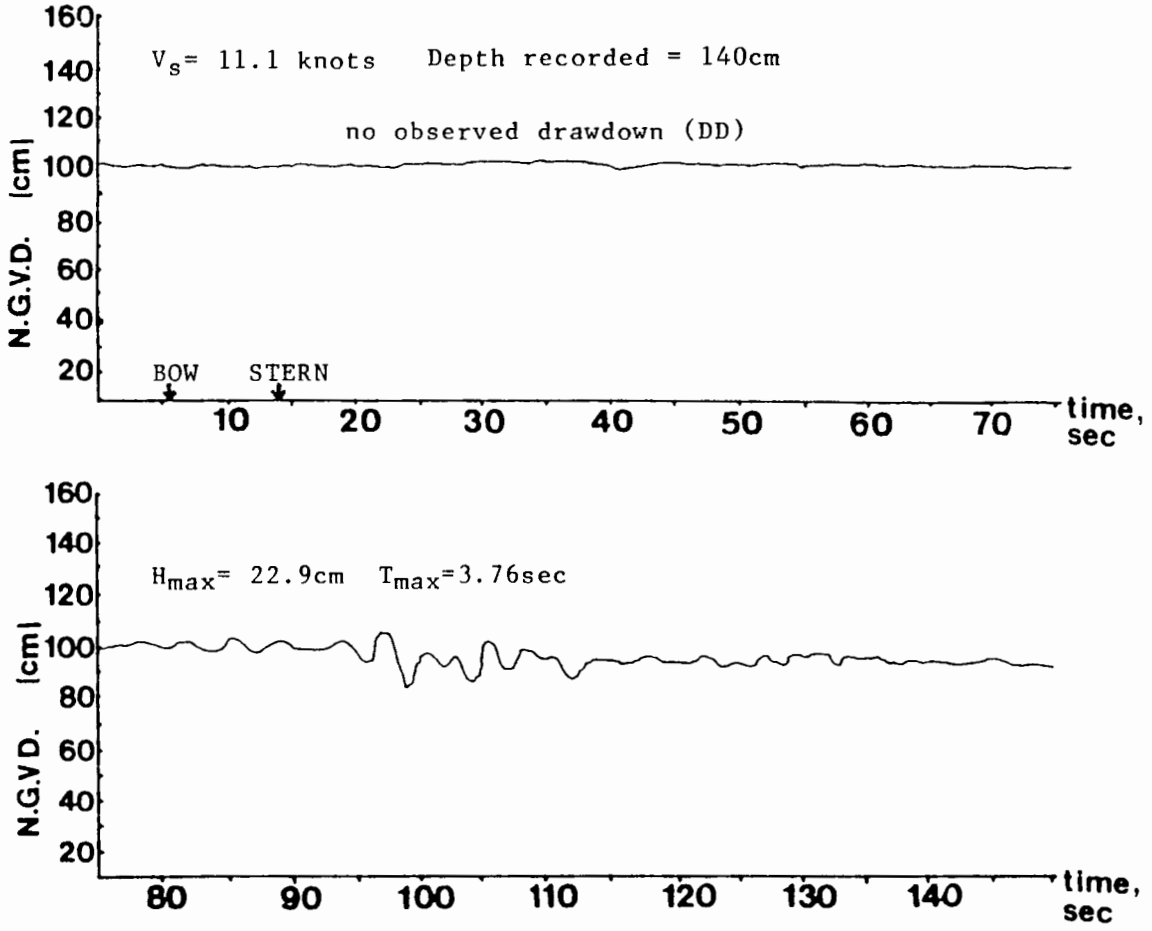
Ship wave record, Puget Island, WA RK 62
Kee Lung 18SEPT87 UPSTREAM 15:35



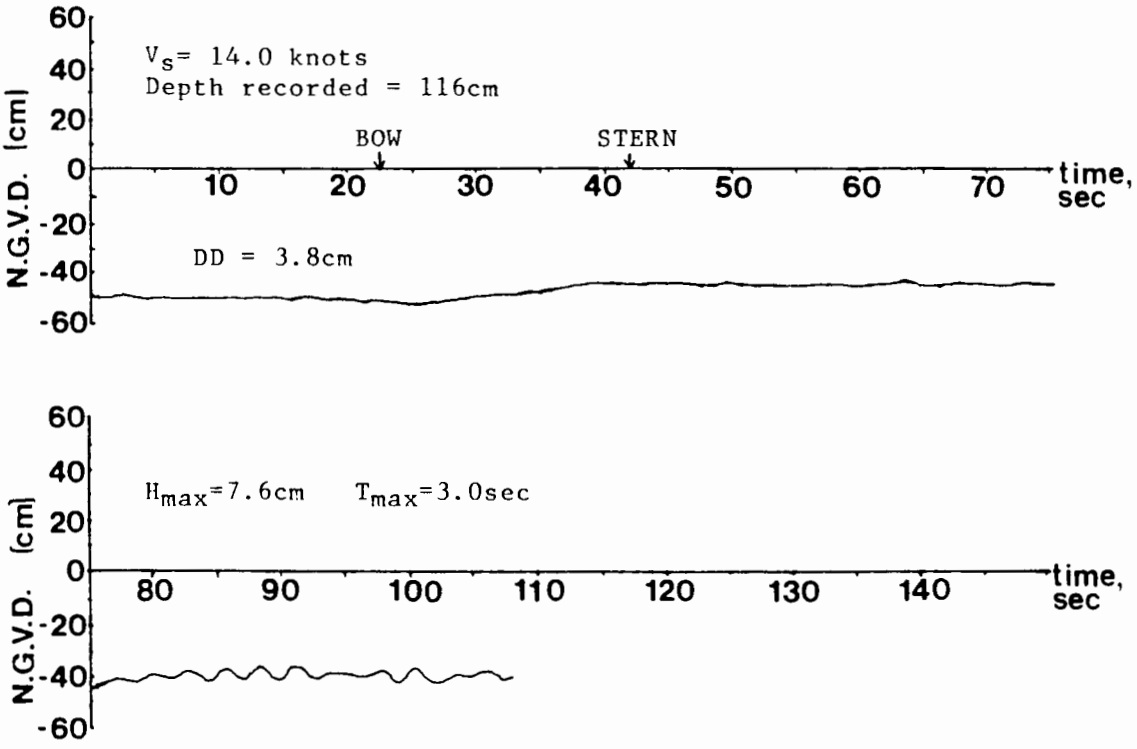
Ship wave record, Puget Island, WA RK 62
Ocean Jade 13JUN88 UPSTREAM 13:10



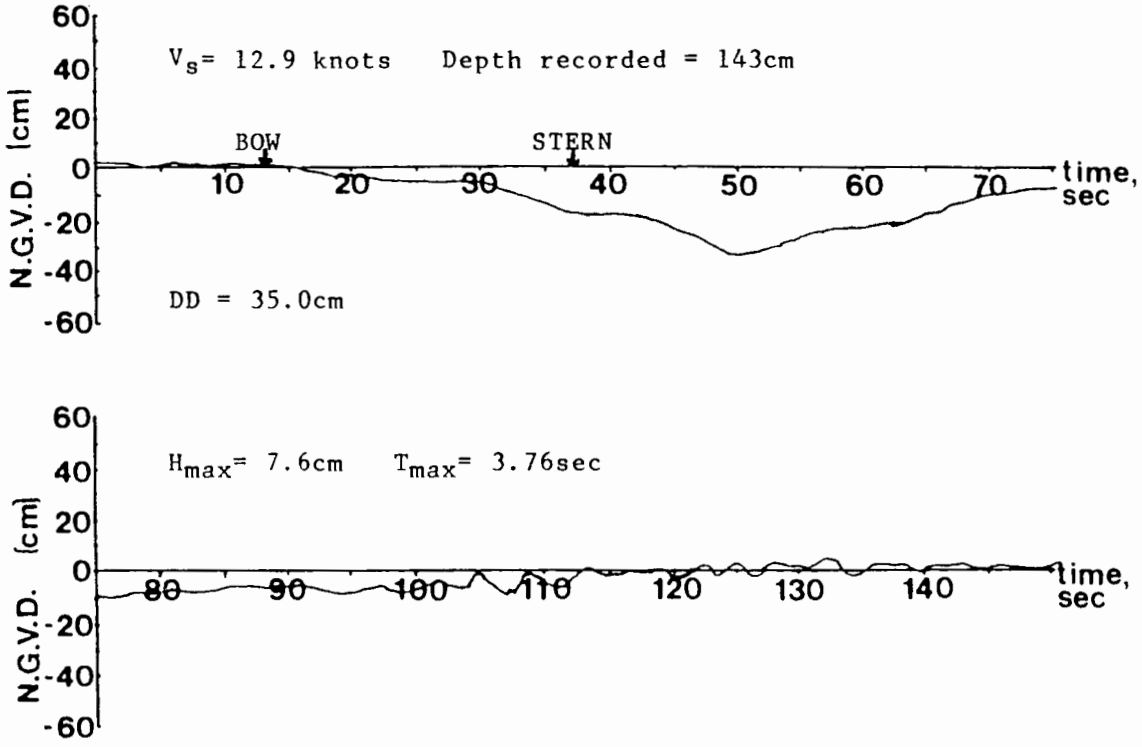
Ship wave record, Puget Island, WA RK 62
U.S.C.G. "Boutwell" (719) 13JUN88 DOWNSTREAM 13:45



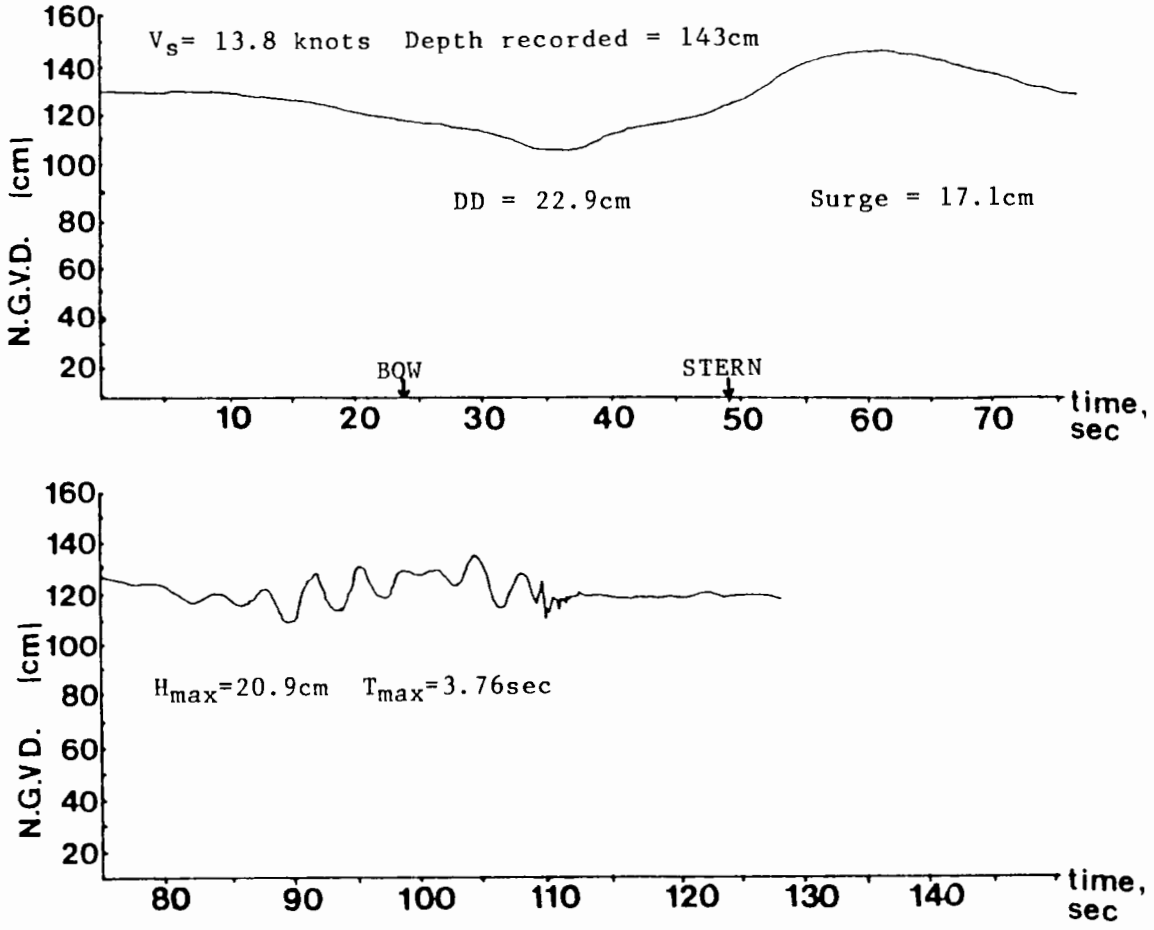
Ship wave record, Puget Island, WA RK 62
U.S.C.G. Bouytender 13JUN88 DOWNSTREAM 13:52



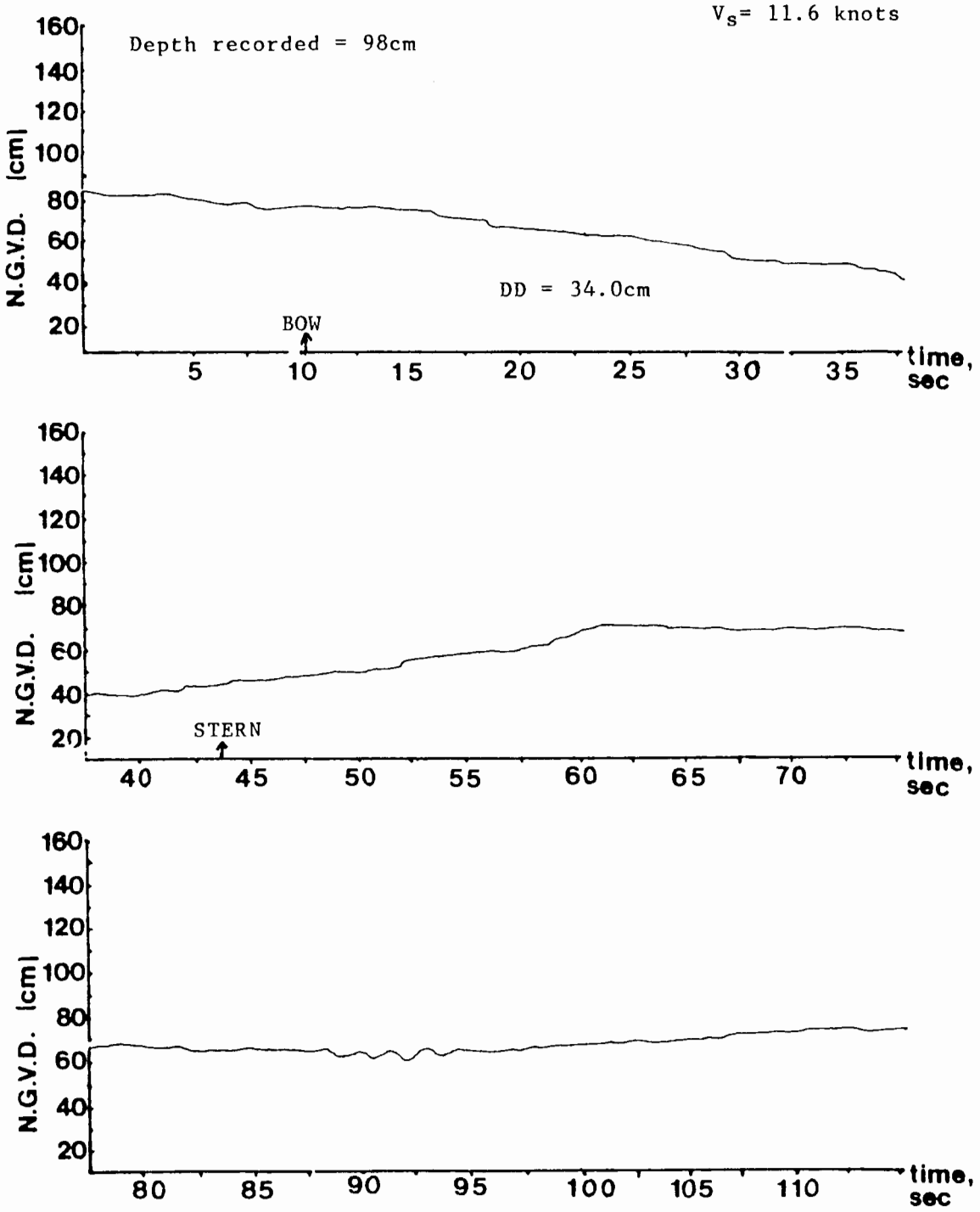
Ship wave record, Puget Island, WA RK 62
USN "Thach" (43) 14JUN88 DOWNSTREAM 11:35



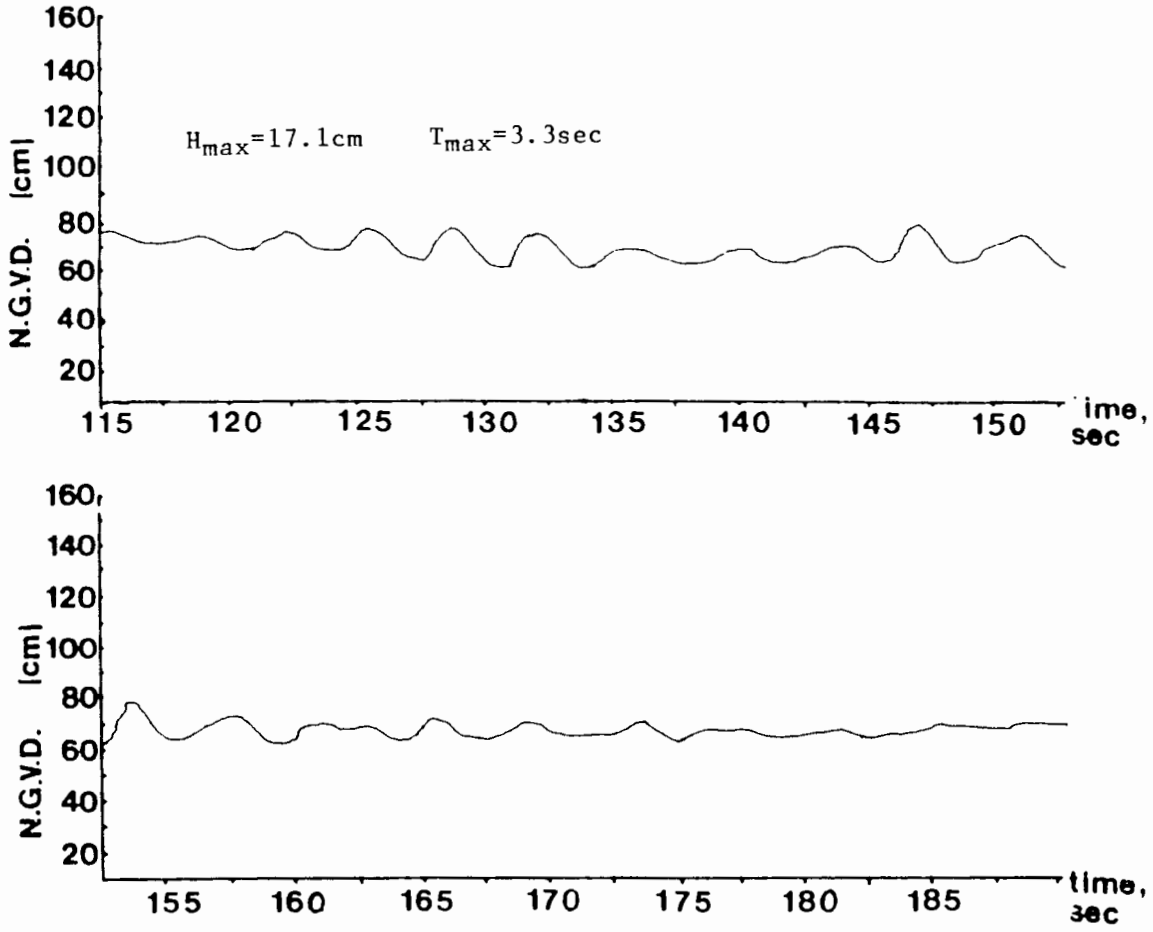
Ship wave record, Puget Island, WA RK 62
Indah Fuji (Happy Eager) 14JUN88 UPSTREAM 12:30



Ship wave record, Puget Island, WA RK 62
USN "Chandler" (996) 14JUN88 DOWNSTREAM 16:00



Ship wave record, Puget Island, WA RK 62
Chevron Oregon 17SEPT87 UPSTREAM 12:54



Ship wave record, Puget Island, WA RK 62
Chevron Oregon 17SEPT87 UPSTREAM 12:54 (continued)

The following eight photographs exhibit water motions in time sequence associated with the passage of a deep-draft ship.

The west end of Wallace Island (RM 47.8-OR) looking west. Note 16-foot (5 m) craft confronting a bore generated by the outbound passage of the container ship "Matsun" at 1230 hours, June 24, 1988. The bore seems to be the result of water just outside the shallow-water region to the left, in the lee of Wallace Island, similar to tidal bore.

Secondary wave train moving into same area. Note vessel in upper right is well past the site. Examining the waves we can deduce that there is a rapid shallowing of the river bottom, where the waves are beginning to break off the end of the island and where you see a rapid reduction in wave length toward the left of the photograph. Decrease in wave length and steepening of wave arc are indicative of waves moving into shallow water.

A fascinating phenomena that is interpreted the reflection of the initial bore or surge off the Oregon side moving back toward Wallace Island. Secondary waves are still attacking shore in foreground as the bore of water displaced by the ship moves toward us.

Surge

Bore starting to retreat off beach face. A complex set of water motions was still being observed all around the site, especially on the shallow water south side.

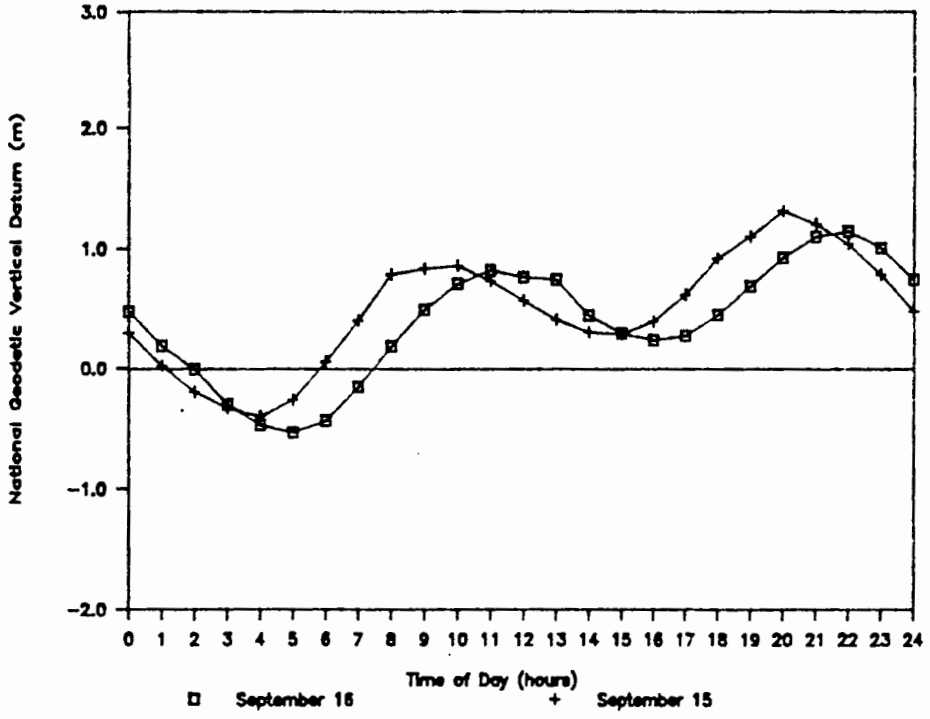
Approximately ten minutes after the vessel initially passed, the site returns to normal conditions. Event reactivated beach scarp on upper portion of beach. This event was one of several spectacular displays of complex water motions and large waves associated with vessel passage, but events such as this were NOT the norm. These large events did seem to be correlated to the downstream passage of large and fast container ships, but this statement cannot be substantiated with the limited data of this study. No equipment, such as the transducer system, was setup to record this event. Wallace Island, June 24, 1988.

"Reflected bore" moving up beach face resembling severe wave runup. Mean water level during the event is just below secondary wave swash occurring in the lower right. Use log in foreground for reference.

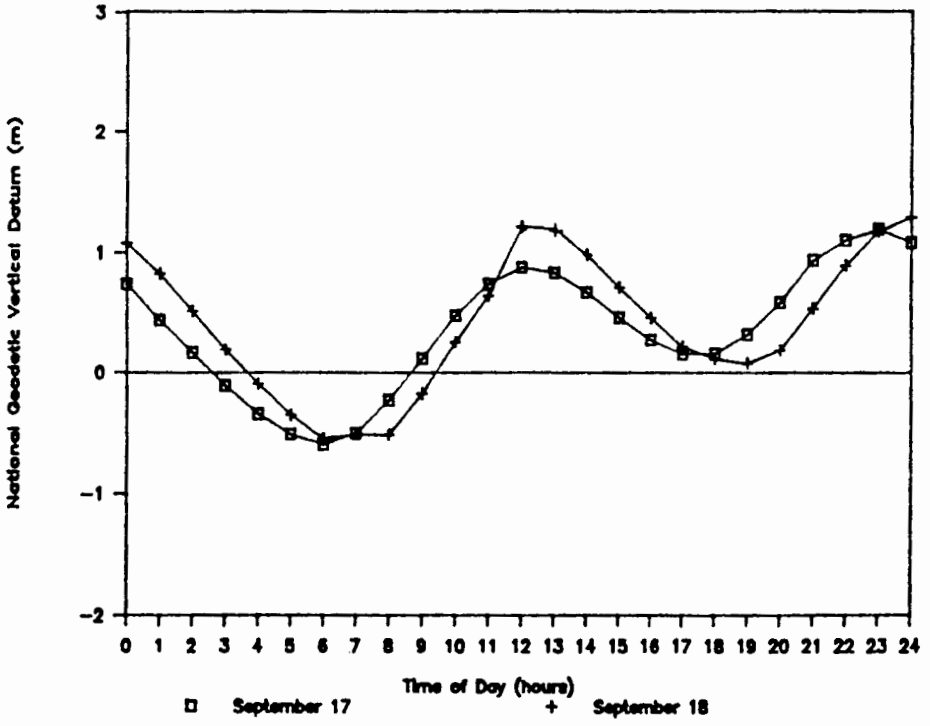
Bore easily reaching base of beach scarp, moving upstream around both sides of the island.

WAVE DESCRIPTION OF VESSEL PASSAGE

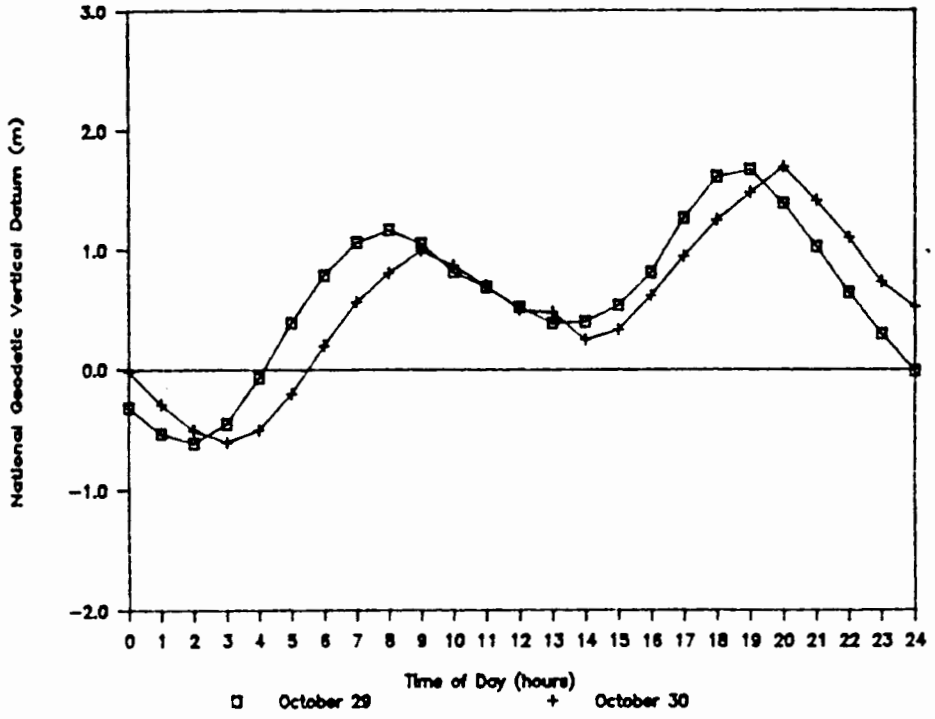
Parameters	S1	S2	S3	S4
Ship	Magnolia	Leandros	Verranzano Bridge	USN Ramsey
Ship Type	bulk	bulk	container	frigate
Direction	upstream	upstream	upstream	upstream
date	09-17-87	10-30-87	06-13-88	06-09-88
time	15:25	13:30	11:33	09:45
River KM	61.4	61.4	61.4	61.4
mean draft	7.0	7.8	6.1	4.6
length	196.0	220.0	264.5	126.3
beam	29.3	32.3	32.3	13.5
displacement	30,127	34,446	18,176	2,640
z_{tide}(NGVD)	0.33m	0.22m	-0.20m	0.90m
A_{ch}	7585m^2	7503m^2	7193m^2	8,005m^2
x_s	225m	225m	225m	225m
v_s	5.61m/s	6.17m/s	6.02m/s	7.9m/s
dd	24cm	27cm	53cm	0
dd_{time}	35sec	30sec	35sec	-
H_{max}	38cm	15cm	19cm	38cm
T_{max}	3.7sec	3.4sec	3.8sec	4.5sec
d_{meas}	150cm	104cm	96cm	168cm
α	15°	17°	0°	7°
bc	.745	.621	.347	.337
bf	.028	.035	.028	.008
m_{beach}	1:22.5	1:18.5	1:12.5	1:11.8



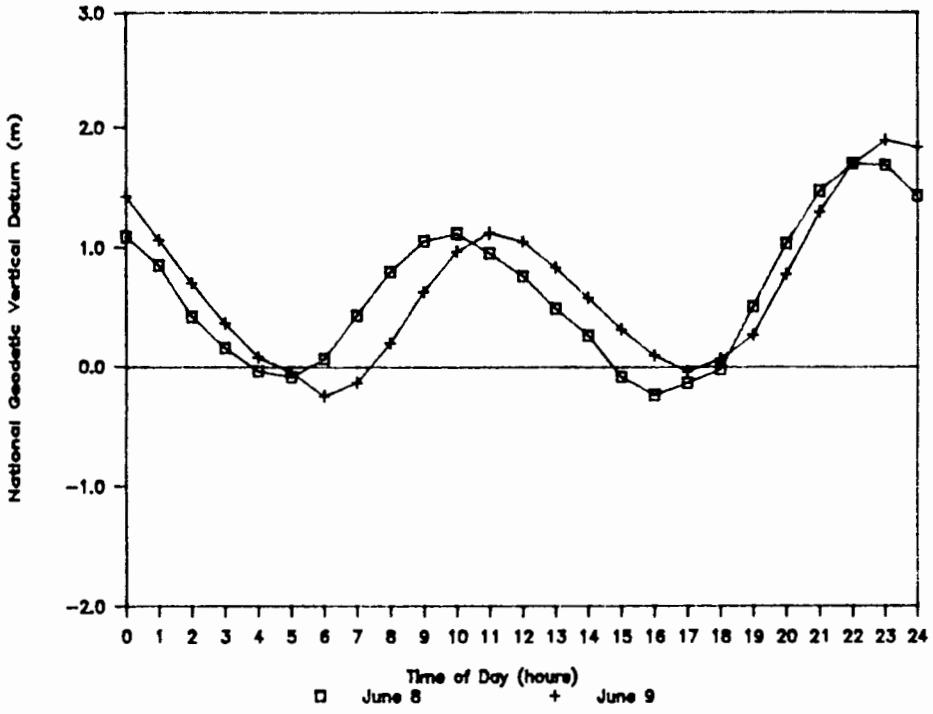
Puget Island Site Tidal Fluctuation
September 15-16, 1987



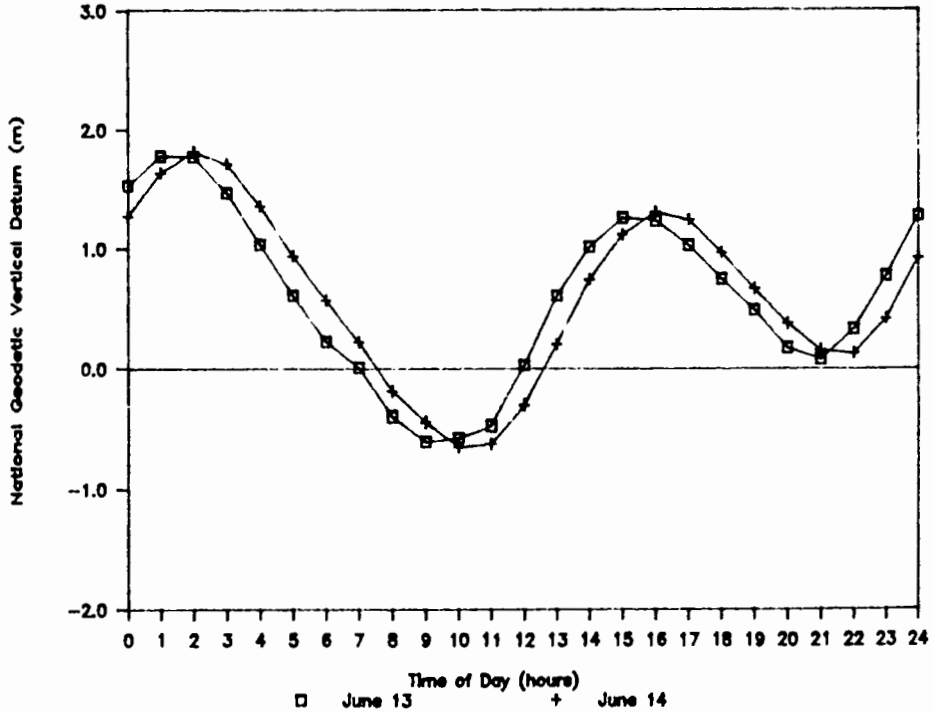
Puget Island Site Tidal Fluctuation
September 17-18, 1987



Puget Island Site Tidal Fluctuation
October 29-30, 1987



Puget Island Site Tidal Fluctuation
June 8-9, 1988



Puget Island Site Tidal Fluctuation
June 13-14, 1988

APPENDIX D

SAND TRANSPORT ON A BEACH FACE

This appendix includes data recorded by the shallow water sediment trap arrays set up on the beach face at the Puget Island site between profiles 9 and 11.

Shallow Water Sediment Trap Array Data

Trap mouth dimension: 3.81*3.81 cm = 14.4 cm^2

ON = Onshore transport, normal to shoreline

OF = Offshore transport, normal to shoreline

DD = Drawdown wave only

LS-D = Longshore transport downstream, parallel to shoreline

LS-U = Longshore transport upstream, parallel to shoreline

Sf = surface sample

α = angle of wave incidence

SHIP	DATE	DIRECTION	
Ocean Beauty	15SEPT87	Upstream 15:17	$\alpha = 5°$

Distance from Shore (m)	Depth (m)	Sampling Direction	SAMPLE DRY WEIGHT (grams) Trap Elevation Above Bed (cm) 1.9	9.5	17.1
5.0	0.26	ON	89.7	8.5	0.8
5.0	0.26	OF	172.4	5.4	0.7
5.0	0.26	LS-U	6.5	0.7	1.0

SHIP	DATE	DIRECTION
Valdiva	15SEPT87	Upstream 16:03 α = 2°

Distance from Shore (m)	Depth (m)	Sampling Direction	SAMPLE DRY WEIGHT (grams) Trap Elevation Above Bed (cm) 1.9	9.5	17.1
3.3	0.17	OF	48.2	1.8	0.2
3.3	0.17	ON	59.9	0.5	0.5

Chevron Oregon	17SEPT87	Upstream 12:54α= 12°

Distance from Shore (m)	Depth (m)	Sampling Direction	SAMPLE DRY WEIGHT (grams) Trap Elevation Above Bed (cm) 1.9	9.5	17.1
5.0	0.26	OF	23.2	1.1	0.4
5.0	0.26	ON	4.7	0.6	0.5
5.0	0.26	LS-U	8.5	2.0	1.0
7.0	0.37	LS-D	0.2	0.1	0.2
10.0	0.52	OF	4.0	0.5	0.03
10.0	0.52	ON	3.0	2.0	0.04

Magnolia	17SEPT	Upstream 15:25 α= 18°

Distance from Shore (m)	Depth (m)	Sampling Direction	SAMPLE DRY WEIGHT (grams) Trap Elevation Above Bed (cm) 1.9	9.5	17.1
5.0	0.26	OF	31.4	13.9	4.4
5.0	0.26	ON	5.1	1.0	0.5
5.0	0.26	LS-U	186.0	117.7	74.5
10.0	0.52	OF	36.0	5.4	3.0
10.0	0.52	ON	26.1	4.0	1.8
10.0	0.52	LS-U	sum of 3 traps = 0.1		

SHIP	DATE	DIRECTION
Cordiality	17SEPT87	Upstream 16:03 $\alpha = 10°$

Distance from Shore (m)	Depth (m)	Sampling Direction	SAMPLE DRY WEIGHT (grams) Trap Elevation Above Bed (cm) 1.9	9.5	17.1
5.0	0.26	OF	23.2	0.4	0.2
5.0	0.26	ON	4.7	1.1	0.5
5.0	0.26	LS-U	8.5	2.0	1.0
10.0	0.52	OF	4.0	1.0	0.03
10.0	0.52	ON	5.4	3.0	2.0
7.0	0.52	LS-U	0.2	0.1	0.0

Evelyn Maersk	18SEPT87	Upstream $\alpha = 21°$

Distance from Shore (m)	Depth (m)	Sampling Direction	SAMPLE DRY WEIGHT (grams) Trap Elevation Above Bed (cm) 1.9	9.5	17.1
5.0	0.26	OF	96.4	11.0	5.4
5.0	0.26	ON	6.1	3.9	1.7
5.0	0.26	LS-U	274.0	45.7	4.2
10.0	0.52	OF	78.0	4.6	0.8
10.0	0.52	ON	33.4	14.8	3.0

SHIP	DATE	DIRECTION
Lake River	29OCT87	Upstream α = 5°

Distance from Shore (m)	Depth (m)	Sampling Direction	SAMPLE DRY WEIGHT (grams) Trap Elevation Above Bed (cm) 1.9	9.5	17.1
5.0		OF	37.7	4.9	1.3
5.0		ON	8.0	0.9	1.2
5.0		LS-U	3.1	1.6	0.8
10.0		OF	16.4	1.3	0.3
10.0		ON	9.2	0.8	0.3

Leandros	30OCT87	Upstream α = 20°

Distance from Shore (m)	Depth (m)	Sampling Direction	SAMPLE DRY WEIGHT (grams) Trap Elevation Above Bed (cm) 1.9	9.5	17.1
5.0		OF	30.3	2.0	0.7
5.0		ON	8.0	1.9	1.2
5.0		DD	18.3	0.1	0.1
5.0		LS-U	23.4	18.9	10.8
10.0		OF	10.5	0.2	0.4
10.0		ON	5.4	0.7	0.5

SHIP	DATE	DIRECTION
European Highway	08JUN88	Upstream 11:15 α = 12°

Distance from Shore (m)	Depth (m)	Sampling Direction	SAMPLE DRY WEIGHT (grams) Trap Elevation Above Bed (cm) 1.9	9.5	17.1
5.8	0.33	OF	283.5	88.1	10.3
5.8	0.33	ON	175.0	52.7	35.7
5.8	0.33	LS-U	14.9	2.4	1.0
12.9	0.73	OF	10.1	4.4	1.5
12.9	0.73	ON	18.7	2.6	1.2
20.0	1.13	LS-U	3.3	0.4	0.1

USN Ford (54)	09JUN88	Upstream 9:07	α = 2°

Distance from Shore (m)	Depth (m)	Sampling Direction	SAMPLE DRY WEIGHT (grams) Trap Elevation Above Bed (cm) 1.9	9.5	17.1
14.0	0.79	OF	102.4	27.4	12.4
14.0	0.79	ON	80.0	21.4	9.7

USN Ramsey (2), and USN 492, 493	09JUN88	Upstream 9:35	α = 5°

Distance from Shore (m)	Depth (m)	Sampling Direction	SAMPLE DRY WEIGHT (grams) Trap Elevation Above Bed (cm) 1.9	9.5	17.1	
10.8	0.61	OF	146.3	81.2	47.2	1.3
10.8	0.61	ON	102.9	26.6	10.5	0.5
10.8	0.61	LS-U	3.1	1.7	1.6	
16.1	0.91	OF	15.8	2.3	0.7	
16.8	0.95	ON	24.9	5.1	0.2	
18.4	1.04	LS-U	1.4	0.2	0.4	

SHIP | DATE | DIRECTION
USN Thach (43) | 09JUN88 | Upstream 10:10 α = 12°

Distance from Shore (m)	Depth (m)	Sampling Direction	SAMPLE DRY WEIGHT (grams) Trap Elevation Above Bed (cm) 1.9	9.5	17.1
7.6	0.43	OF	334.8	170.4	94.4
7.6	0.43	ON	56.0	31.4	14.5
8.7	0.49	LS-U	50.0	30.0	12.2
12.9	0.73	OF	33.9	1.7	0.8
14.0	0.79	ON	38.0	2.1	1.1
14.0	0.79	failed			

USN Gray (1054) 09JUN88 Upstream Time 10:23 α= 7°

Distance from Shore (m)	Depth (m)	Sampling Direction	SAMPLE DRY WEIGHT (grams) Trap Elevation Above Bed (cm) 1.9	9.5	17.1
7.6	0.43	OF	785.0	309.9	136.0
8.1	0.46	ON	219.3	116.9	75.7
9.2	0.52	LS-U	20.3	1.5	0.7

Coast Range 09JUN88 Upstream 13:00 α = 1°

Distance from Shore (m)	Depth (m)	Sampling Direction	SAMPLE DRY WEIGHT (grams) Trap Elevation Above Bed (cm) 1.9	9.5	17.1
5.0	0.33	OF	253.9	85.9	25.7
5.0	0.36	ON	166.5	74.1	26.6
5.0	0.33	DD	53.8	0.1	0.05
10.0	0.70	OF	11.7	0.6	0.65
10.0	0.76	ON	8.4	3.9	1.0
14.0	0.98	OF	6.0	0.3	0.4

SHIP: Coast Guard, Boutwell (719, Cutter) and Iris (Buoytender) — DATE: 13JUN88 — DIRECTION: Downstream Time 11:00 α= 16°

Distance from Shore (m)	Depth (m)	Sampling Direction	SAMPLE DRY WEIGHT (grams) Trap Elevation Above Bed (cm) 1.9	9.5	17.1
5.0	0.35	OF	112.6	59.2	15.2
5.0	0.35	ON	45.3	1.3	3.2
5.0	0.35	LS-D	62.0	49.5	15.0
10.0	0.70	OF	10.8	1.0	0.7
10.0	0.70	ON	31.2	26.6	0.4
10.0	0.70	LS-D	1.0	0.2	0.1

Verrazano Bridge — 13JUN88 — Upstream 11:33 — α =3°

Distance from Shore (m)	Depth (m)	Sampling Direction	SAMPLE DRY WEIGHT (grams) Trap Elevation Above Bed (cm) 1.9	9.5	17.1
5.0	0.35	ON	8.9	1.8	0.7
5.0	0.35	OF	20.0	1.1	0.2
5.0	0.35	LS-U	0.6	0.3	0.2
10.0	0.70	OF	18.5	0.1	0.3
10.0	0.70	ON	1.8	0.3	0.1
10.0	0.70	LS-U	1.0	0.1	0.0

SHIP	DATE	DIRECTION		
Verrazano Bridge*	14JUN88	Downstream	16:40	$\alpha = 21°$

Distance from Shore (m)	Depth (m)	Sampling Direction	SAMPLE DRY WEIGHT (grams) Trap Elevation Above Bed (cm) 1.9	9.5	17.1
11.0	0.76	LS-D	410.0	58.9	14.5
14.4	1.01	LS-D	335.9	49.1	14.9

*Because of large waves, traps were dislodged and data was disregarded.

RIVER FLOW SAND TRANSPORT IN THE NEAR SHORE REGION

06/14/89 11:10-11:22
(3cm rise in water surface in that time)

Distance from Shore (m)	Depth (m)	Sampling Direction	SAMPLE DRY WEIGHT (grams) Trap Elevation Above Bed (cm) 1.9	9.5	17.1
10.4	0.73	LS-D	0.2	0.2	0.3
13.6	0.95	LS-D	15.2	0.1	0.1
17.0	1.19	LS-D	33.8	0.5	0.5

surface velocity at 1.22 m, 10:52 hrs.= 27.5 cm/s downstream

06/14/88 14:07-14:17

Distance from Shore (m)	Depth (m)	Sampling Direction	SAMPLE DRY WEIGHT (grams) Trap Elevation Above Bed (cm) 1.9	9.5	17.1
8.3	0.58	LS-U	0.1	0.0	0.0
10.6	0.76	LS-U	0.2	0.1	0.0
13.0	0.91	LS-U	5.9	0.2	0.1

surface velocity at 0.91 m, 13:50 hrs. = 14.1 cm/s upstream
1.22 m, 13:56 hrs. = 15.1 cm/s upstream